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AI and 6G Into the Metaverse: Fundamentals, Challenges and Future Research Trends

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AI and 6G Into the Metaverse: Fundamentals, Challenges and Future Research Trends

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ABSTRACT Since Facebook was renamed Meta, a lot of attention, debate, and exploration have intensified about what the Metaverse is, how it works, and the possible ways to exploit it. It is anticipated that Metaverse will be a continuum of rapidly emerging technologies, usecases, capabilities, and experiences that will make it up for the next evolution of the Internet. Several researchers have already surveyed the literature on artificial intelligence (AI) and wireless communications in realizing the Metaverse. However, due to the rapid emergence and continuous evolution of technologies, there is a need for a comprehensive and in-depth survey of the role of AI, 6G, and the nexus of both in realizing the immersive experiences of Metaverse. Therefore, in this survey, we first introduce the background and ongoing progress in augmented reality (AR), virtual reality (VR), mixed reality (MR) and spatial computing, followed by the technical aspects of AI and 6G. Then, we survey the role of AI in the Metaverse by reviewing the state-of-the-art in deep learning, computer vision, and Edge AI to extract the requirements of 6G in Metaverse. Next, we investigate the promising services of B5G/6G towards Metaverse, followed by identifying the role of *AI in 6G networks* and *6G networks for AI* in support of Metaverse applications, and the need for sustainability in Metaverse. Finally, we enlist the existing and potential applications, usecases, and projects to highlight the importance of progress in the Metaverse. Moreover, in order to provide potential research directions to researchers, we underline the challenges, research gaps, and lessons learned identified from the literature review of the aforementioned technologies.

INDEX TERMS Metaverse, 5G, 6G, AI, cloud and edge computing, AR/VR/XR, spatial computing.

I. INTRODUCTION

IN 2021, Metaverse started influencing the real-world due to: i) pandemic lifestyle, and ii) the announcements of

Meta, Amazon, Apple, Netflix, and Google (MAANG) to release Metaverse-related features and projects for their users. Since then, Metaverse has sought sheer attention

from both academia and industry. At the current point in time, the Metaverse can be generally viewed as a pool of extended reality (XR)¹ spaces in which humans and their digital counterparts interact in a fully immersive manner [1], [2], [3], [4]. According to a recent survey,² the majority of technology experts believe that by 2040 the Metaverse will be more refined and seamless in its operation so that people around the world will be able to fully engage in its full immersion capabilities as an integral part of their daily lives. In essence, Metaverse is anticipated to integrate all essential aspects of cyberspace or the world wide Web, such as B5G/6G, cloud and edge computing, social media, online gaming, augmented reality (AR), virtual reality (VR), cryptocurrencies, and artificial intelligence (AI)/machine learning (ML)/deep learning (DL) platforms and applications, to allow users to interact virtually [1], [5], [6], [7], [8].

Some of the early stage applications of Metaverse, namely Roblox,³ VRChat,⁴ Zepeto⁵ or Second Life⁶ have been allowing users to live in “different” or simulated lives, such as making friends and socializing with new avatars. These platforms have incorporated AR, VR and MR as a few elements of the Metaverse. The VR technology replaces the real world around users with a computer-generated digital scene using various software and communication devices, such as a head-mounted display (HMD). While in AR, the virtual world is seamlessly connected with the real world in order to create new interactive experiences. Finally, MR emerges as the combination of AR and VR and their underlying technologies. It is also noteworthy to mention that the popularity of these technologies has led to the universal availability of AR and VR equipment at reasonable prices while continually improving the quality of experience (QoE) for their users [9].

However, in order to achieve the processing power and communication speed that are required by VR services to deliver smooth and immersive experiences, most HMDs still require the users to be tethered to a PC or gaming console. The only device to break free from this cable constraint is Meta’s Oculus Quest 2.⁷ *Over the next few years, a number of improvements will be made to visual content and the untethered experience of mobile devices as processors get faster and wireless communication technologies to become latency-free.* In particular, with the existence of 5G, there will be a proliferation of devices connected to the network, which will have a profound impact on the growth of Metaverse [10]. 5G has enabled real-time communication and information exchange among all of the connected devices with its low

latency. It is evident that 5G offers faster speeds than 4G, but most importantly, it offers a variety of other benefits that go beyond speed alone [11]. Specifically, Metaverse developers will be able to benefit from 5G’s low latency by creating applications that can transmit 360° content in near real-time.

Metaverse will also proliferate the trend of human-centric/data-centric intelligent systems. This trend poses a number of constraints on existing 5G communication systems, making them less efficient and unreliable. For example, considering the 0.1ms delay requirements of haptic-based Metaverse applications such as teleportation or teleoperations, 5G can only provide the air interface latency of <1ms, which becomes inconsiderable for such applications [12], [13], [14], [15]. Moreover, according to Cisco [16], mobile data traffic has grown 17-fold over the past five years and is expected to continue to grow. In particular, as of 2022, the 5G traffic will comprise 12% of the total mobile traffic in the world. 5G networks were designed to be able to cover large areas of the spectrum, such as millimeter-waves (up to 300 GHz), and as a result, can handle large quantities of wireless traffic [17], [18], [19], [20].

Since Metaverse will bring several applications that may require data rates that are higher than Tbps, which is not likely to be the case with mmWave systems, such as holographic telepresence (HT), haptic sensory communications, brain-computer interface (BCI), and XR [21], [22], [23]. As a result, researchers have resorted to exploring the Terahertz (THz) frequency band (0.1-10 THz) in order to achieve the objectives of Tbps data rates. 6G communication system is expected to provide 1Tbps of data rates, operating at 3Thz of bandwidth in order to support data-intensive applications such as online gaming, live streaming of high definition videos, the transmission of holographic content, and real-time avatar interactions [24], [25], [26], [27]. 6G will also provide ubiquitous coverage and ultra-low latency (less than 1ms) as well as support around 100 km/hour mobility by integrating the space-air-ground-sea networks [28], [29], [30].

Nevertheless, Metaverse applications such as virtual education and training, precise navigation and localization, immersive gaming, and remote healthcare applications would all be enabled by AI and 6G, making the Metaverse more successful. In particular, state-of-the-art in computer vision can be utilized to provide animated 3D human models or realistic animated faces, and even for the creation of holograms [31], [32], [33]. However, the key challenge in utilizing the 3D content for Metaverse services lies in the scalability of the existing infrastructure. Therefore, the rise of Metaverse makes it crucial to develop the key tools and infrastructure to enable Metaverse developers to build better and more scalable 3D/AR/VR experiences, regardless of platforms or purposes. In principle, researchers need to take a leap from the supervised learning paradigm of AI and resort to diversified learning strategies such as reinforcement learning and self-supervised learning in order

1. Note that important acronyms are defined in Table 1.

2. <https://www.pewresearch.org/internet/2022/06/30/the-metaverse-in-2040/>

3. <https://www.roblox.com/>

4. <https://hello.vrchat.com/>

5. <https://zepeto.me/>

6. <https://secondlife.com/>

7. <https://store.facebook.com/ie/quest/products/quest-2/>

TABLE 1. List of important acronyms.

Acronym	Definition
AI	Artificial Intelligence
AIInfra	AI-based Infrastructure
AIInt	AI-based Interfaces
AICont	AI-based Smart Contracts
AIVWorld	AI-based virtual worlds
AIART-E	AI-based Art for economic enrichment
AR	Augmented Reality
B5G and 6G	Beyond 5G and Sixth-Generation
CPS	Cyber-Physical Systems
DT	Digital Twin
DL	Deep Learning
eRLLC	Extremely Reliable and Low Latency Communications
eMBB	Enhanced Mobile Broadband
FL	Federated Learning
FCC	Federal Communications Commission
FoV	Field of View
FPS	Frames per second
GPU's	Graphical Processing Units
GBs and GHz	Gigabytes and Gigahertz
GauGAN	Paul Gauvin Generative Adversarial Networks
GPT	Generative Pre-trained Transformer
HDR	High Dynamic Range
HMD	Head-mounted Display
HCI	Hyper-computer Interface
HT	Holographic Telepresence
HEMTs	High-electron-Mobility Transistors
ICT	Information and Communications Technology
IoT	Internet of Things
IIoT	Industrial Internet-of-Things
KPI	Key Performance Indicator
LTE	Long Term Evolution
mMIMO	Massive Multiple-Input and Multiple-Output
mLLMTC	Massive Low Latency Machine Type Communication
ML	Machine Learning
MEC	Multi-access Edge Computing
NIB	Network-in-Box
NFV	Network Functions Virtualization
NLP	Natural Language Processing
O-RAN	Open Radio Access Networks
PersonalizedAI	AI for personalized immersive experience
QoS and QoE	Quality-of-Services and Quality-of-Experiences
RIS	Reflecting Intelligent Surfaces
RSI	Real Super Intelligence
SDN	Software-defined Networking
SAGSIN	Space-air-ground-sea Integrated Network
SocialAI	Improved social network experience with AI
THz and mmWave	Terahertz and Millimeter Wave
TI	Tactile Internet
UAVs	Unmanned Aerial Vehicles
UmMTC	Ultra-massive Machine Type Communication
VR	Virtual Reality
XR	Extended Reality
3GPP	3rd Generation Partnership Project

to scale in a Metaverse environment. Moreover, the edge computing capabilities of 6G networks can be combined with the AI to provide edge intelligence, hence reducing the network delays and privacy issues for enhanced QoE in Metaverse [34]. *Motivated by the existing technologies and foreseen challenges, we survey the state-of-the-art in AI and 6G in the context of Metaverse to answer the following question: how to provide a better and sustainable Metaverse experience by leveraging the ongoing progress in AI, 6G, and the nexus of both?* In the following subsections, we review the related surveys and outline the contribution and structure of this survey.

A. RELATED SURVEYS

In this subsection, we review the state-of-the-art surveys conducted on several technologies in the context of Metaverse. Recently, there has been many surveys and research studies conducted to investigate the potential technology, its implementation, applications, and future research directions [1],

[2], [3], [4], [6], [10], [30], [35], [36], [37], [38], [39], [40], [41], [42]. For example, Yang et al., [35] investigate the integrated role of AI and Blockchain for the Metaverse environments. In particular, authors in [35] propose that Metaverse is a 3D virtual reality platform that covers all aspects of social and economic activities and allows everyone to participate in these activities in a safe and free environment that transcends the limitations of our real world by making use of AI and blockchain technology. Similarly, [2] and [43] surveys the security and privacy concerns for Metaverse users and proposes potential directions to provide secure services to Metaverse users. On the other hand, researchers in [3], [36], [37] investigate the role of AI in the Metaverse. In particular, [3] surveys the existing state-of-the-art in AI, computer vision, and deep learning in the context of Metaverse, while [36] and [37] explore the role of edge intelligence and 6G-powered edge AI for Metaverse, respectively. In contrast, authors in [1], [30], [39], [40] scrutinize the wireless communication architectures and technologies in support of Metaverse. For instance, [30] reviews the advancements in ultra reliable and low latency communication (uRLLC), digital twins, and SAGSIN for providing ubiquitous intelligence in Metaverse, while [40] and [39] provides the overview of Mobile Edge Computing (MEC) and Internet of Everything (IoE) for Metaverse. Different from above studies, authors in [2], [3], [4], [41], [42] provide the overview of societal, economical, technological, and digital value in Metaverse applications. In Table 2, we compare and contrast the above-discussed state-of-the-art with this article in terms of different aspects of Metaverse.

B. METHODOLOGY OF THIS SURVEY

To ensure the comprehensiveness and relevance of the surveyed literature, our methodology covered an extensive timeframe, ranging from January 1995 to December 2022. We present details in Table 3. We meticulously searched for articles in esteemed databases including IEEE Xplore, Scopus, Science Direct, and Google Scholar. The selected articles consisted of early access materials and published peer-reviewed research from technical conferences and journals. Our screening procedures were designed to focus on the core elements of each paper relevant to our research topics. We assessed the significance of the literature through a thorough examination of its abstract, introduction, and conclusion. This approach enabled us to maintain a high standard of quality and relevance in the selected literature.

While our search strings aligned with the themes of our paper, encompassing keywords related to the Metaverse, AI, 6G, and their associated technologies, we ensured that the selected works provided a holistic view of these subjects. Our methodology encompasses a wide array of relevant keywords, including those such as “6G-powered Edge AI”, “XR for Metaverse”, “IoT/IoE in Metaverse”, “mobile edge computing for Metaverse”, “uRLLC for VR/XR”, “human-centric Metaverse”, “user interactions and implementations”,

TABLE 2. Summary and categorization of the reviewed studies concerning Metaverse.

Authors & Year	Reference Numbers	AR, VR, XR, Spatial Computing	Layered Metaverse Architecture	Computer Vision and Learning Paradigms	5G/6G, MEC, mmWave, THz	AI for 6G Networks	6G networks for AI	Sustainability	Applications and Usecases	Frameworks, Projects & Demos	Challenges, Research Directions, & Lessons Learned	Remarks (Relevance with Metaverse)
Yang <i>et al.</i> , 2022	[35]	L	X	✓	X	X	X	M	X	X	M	Integration of Blockchain and AI for Metaverse
Wang <i>et al.</i> , 2022	[36]	M	X	L	✓	X	X	L	✓	L	✓	Security and Privacy for Metaverse
Huynh <i>et al.</i> , 2022	[37]	✓	X	✓	L	✓	L	L	✓	M	M	Artificial Intelligence for Metaverse
Lim <i>et al.</i> , 2022	[10]	✓	✓	M	✓	M	✓	L	L	L	✓	Edge Intelligence for Metaverse
Khan <i>et al.</i> , 2022	[1]	L	X	L	✓	X	✓	L	M	L	L	Wireless Architectures for Metaverse
Chang <i>et al.</i> , 2022	[38]	L	L	L	✓	L	✓	X	M	L	M	6G-powered Edge AI for Metaverse
Jagatheesaperumal <i>et al.</i> , 2022	[39]	✓	X	X	L	X	L	L	✓	L	✓	XR and IoE for Education in Metaverse
Dhelim <i>et al.</i> , 2022	[40]	L	L	L	✓	L	✓	X	M	X	L	Mobile Edge Computing for Metaverse
Park <i>et al.</i> , 2022	[41]	✓	X	✓	L	✓	L	L	✓	M	M	User interactions, Implementations, and Applications in Metaverse
Tang <i>et al.</i> , 2022	[30]	L	X	L	M	L	✓	X	X	X	✓	URLLC, Digital Twins, and SAGSIN for Metaverse
Gadekallu <i>et al.</i> , 2022	[6]	✓	X	L	L	X	X	L	L	✓	✓	Blockchain Technology for Metaverse
Mozumder <i>et al.</i> , 2022	[42]	L	X	L	L	M	M	X	X	X	X	Technology Roadmap for Healthcare in Metaverse
Ning <i>et al.</i> , 2021	[2]	✓	X	M	L	X	X	M	✓	✓	✓	Social Value and Technology convergence in Metaverse
Lee <i>et al.</i> , 2021	[3]	✓	M	✓	M	L	L	M	✓	L	✓	Technological Ecosystem for Metaverse
Lee <i>et al.</i> , 2021	[4]	✓	L	✓	X	X	X	L	M	✓	M	Digital Artworks for Metaverse
Our Article	—	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	This survey investigates the underlying technologies of AI and 6G, such as advancements in computer vision, learning paradigms, and wireless communication technologies in the context of Metaverse. The joint role of AI and 6G in obtaining ubiquitous intelligence, tactile feedbacks, and self-optimising capabilities for Metaverse is explored. The sustainability aspect of Metaverse followed by the applications, usecases, and on-going projects is given. Lastly, numerous open issues, future directions, and lessons learned are enlightened for potential researchers and developers of Metaverse applications and services.

✓ High Coverage M Medium Coverage L Low Coverage X Absent/Unavailable

TABLE 3. Methodology on screening papers.

Searching Index	Content and Evaluation
Search Time-period	From: January 1995, To: December 2022
Article Database	IEEE Xplore, Scopus, Science Direct, and Google Scholar.
Articles Type	Early Access and Published Peer-reviewed Technical Conferences and Journals.
Screening Procedures	Each paper's relevance to the research topic is determined by its abstract, introduction, and conclusion.
Search Strings	"6G-powered Edge AI", "XR for Metaverse", "IoT/IoE in Metaverse", "mobile edge computing for Metaverse", "URLLC for VR/XR", "human-centric Metaverse", "user interactions and implementations", "SAGSIN for VR/XR", "blockchain for VR/XR", "digital twin", "social value in AR/VR/XR", "sustainability in AR/VR/XR", etc.

"SAGSIN for VR/XR", "blockchain for VR/XR", "digital twin", "social value in AR/VR/XR", "sustainability in AR/VR/XR", among others. These search strings facilitated the inclusion of comprehensive and contemporary literature that aligns with the diverse aspects of the Metaverse, as discussed in our survey paper.

C. CONTRIBUTION AND STRUCTURE OF THIS SURVEY

It is clear from the above discussion that some of the existing surveys have focused on very narrow perspectives of AI, 6G, and relevant technologies, while others have investigated the

role of the Metaverse in terms of societal, economic, and digital value. As opposed to them, in this review, we provide the following key contributions:

- We describe the underlying components of Metaverse, i.e., VR, MR, AR, and Spatial computing. The fundamentals of the aforementioned technologies are presented to provide readers with an understanding of technical aspects and state-of-the-art, leading to a fully immersive Metaverse.
- We present an extensive review of the state-of-the-art in AI and examine the role of AI in realizing the Metaverse with an aim to extract communication requirements for 6G in Metaverse. Essentially, we define the role of AI in the layered architecture of Metaverse, followed by the state-of-the-art in computer vision applications, learning paradigms and Edge AI for Metaverse.
- We explain the role of B5G/6G in realizing Metaverse by firstly answering the following key questions: i) *is B5G/6G need of an hour?* and ii) *what services B5G/6G can bring to Metaverse?* Next, we review the state-of-the-art for immersive experiences and holographic telepresence over wireless by exclusively

considering the role of 5G-NR, URLLC, mmWave, MEC, THzComms, and their interplay.

- We also consider the integrated role of AI and 6G towards realization of the Metaverse. In principle, we examine the potential of *AI for 6G networks* and *6G networks for AI* in support of Metaverse. Next, we investigate the sustainability of Metaverse in the context of the aforementioned technologies, followed by the potential applications and usecases and ongoing projects. Lastly, we present the challenges and future research directions along with the lessons learned from this survey.

The rest of the article is organized as follows. Section II includes the background and technical aspects of all relevant technologies, including AI, 6G, VR, MR, AR, and Spatial computing. Section III presents the role of AI in the Metaverse, while Section IV covers the role of B5G/6G in the Metaverse. Section V highlights the integrated role of AI and 6G in the context of Metaverse, followed by the sustainability perspective of Metaverse in Section VI. Applications and Usecases are explored in Section VII, followed by the description of projects in Section VIII. Challenges and future research directions are entailed in Section IX, while Section X presents the lessons learned from this survey. Finally, Section XI concludes the survey. In Figure 2, we present our paper's complete pictorial structure.

II. AI AND 6G FOR METAVERSE: BACKGROUND AND TECHNICAL ASPECTS

This section of the article will provide a detailed account of the background on the metaverse from the point of view of technical analysis. The term “Metaverse” is a combination of the prefix “meta” (meaning “beyond”) and the suffix “verse” (short for “universe”). As a result, it refers to a universe beyond the physical world. This “universe beyond” alludes to a computer-generated environment instead of metaphysical or mystical notions of domains beyond the physical reality [44]. Metaverses are fully immersive three-dimensional digital environments, as opposed to cyberspace, which refers to all online spaces. We provide a critical evaluation of AI and the Metaverse in this section and some essential prerequisites for understanding the Metaverse 6G prospects [45]. This comprehensive overview will cover the fundamental algorithms, terminology, and current and future product applications. We take a brief introduction to AI, which constructed a sophisticated black-box for high-level tasks such as detection and classification. The Metaverse role is then conducted to investigate what the Metaverse requires of AI key stakeholders for more trustworthy communications [46].

A. DEFINITION OF METAVERSE BASED ON AI AND 6G

Metaverse is an advanced digital realm that incorporates artificial intelligence and 6G technology to provide users with highly realistic, personalized, and interactive experiences. A highly immersive shared environment is created

by combining artificial intelligence with ultra-fast and low-latency wireless communication to create dynamic virtual environments. Metaverse allows users to participate in activities such as shopping, gaming, and socializing. It also allows users to explore virtual universes, create virtual objects, and customize their avatars. Metaverse is revolutionizing the way people interact with technology and is the future of virtual interaction. It is predicted to have a huge economic impact in the coming years. Metaverse is also poised to revolutionize the way we work, allowing people to work remotely and collaborate more effectively. It is also expected to create new opportunities for people to earn a living, as well as enable businesses to reach a wider audience.

B. THE BACKGROUND OF AI FOR METAVERSE

This section explain the background of metaverse. The metaverse incorporates numerous technologies such as 3D animation, VR, AR, spatial computing, blockchain, and many more hot technologies [49], [50]. It is the next technological future from a socioeconomic standpoint. Many enterprises have already devoted significant resources to Metaverse initiatives to give new digital services to the globe and be the first to deliver metaverse landscapes. Why do we say metaverse is the hottest technological and socioeconomic topic right now? Take the example of Facebook, which changed its name to Meta from Facebook, demonstrating that the metaverse will be the next big mainstream technology for industries. The future of Internet in metaverse will be a large-scaled, resilient, dynamic, and platform for socializing, trading, transferring data, and entertaining people in real-time. Hitherto, a lot of effort was made on Web1 and Web2 [51]. Web1 was guided on browsing plain online pages, whereas Web2 explained how to connect to social platforms within controlled ecosystems. In the metaverse, NFTs will take the place of digital ownership in an open, decentralized environment [52]. This will enable people to link digitally with the rest of the world and generate a healthy economy in which people can execute any work that can be performed in the physical world. Much has been said about the Internet and its future, but it is vital to distinguish between the metaverse and Web3. Web3 is about applying advanced digital services, but instead of being controlled by large technology corporations as in Web2, these services will be created and governed by the community, returning to the ethos of Web1, when the Internet's value was generated by users at the network's edge, predominantly in a forward mode. Virtual worlds, massive scalability, persistence, synchronicity, a functional economy, openness and decentralization, interoperability, and so on should all be included in a Metaverse platform [46]. The metaverse begins to make artificial intelligence (AI) more ubiquitous in reality, which will power numerous metaverse technology layers such as spatial computing, artist scaffolding, and new emerging types of storytelling. We have seen that AI is advancing at a comparable level, such as transformers; transformers are neural networks that allow

TABLE 4. Definition of Metaverse based on AI and 6G from different survey papers.

Reference	Years	Definition	Applications
[37]	2023	A variety of artificial intelligence techniques are used for the metaverse, including traditional machine learning algorithms and emerging deep learning architectures, as well as supervised, unsupervised, and reinforcement learning strategies.	✓
[35]	2022	A preliminary look at the metaverse economy, a discussion of how blockchains and artificial intelligence can be integrated, and a review of current research in the field are presented.	×
[4]	2021	The Metaverse is a virtual space for creators and artists to reshape our virtual and physical environments.	✓
[47]	2021	The metaverse technology framework outlines the challenges and opportunities for research based on the ultimate stages of the metaverse.	×
[36]	2022	Author examines the security and privacy threats in the metaverse from seven perspectives and discusses how to address them.	×
[48]	2022	This article examines the concept of the metaverse and proposes that it is a super virtual reality (VR) ecosystem in comparison with other VR technologies	×

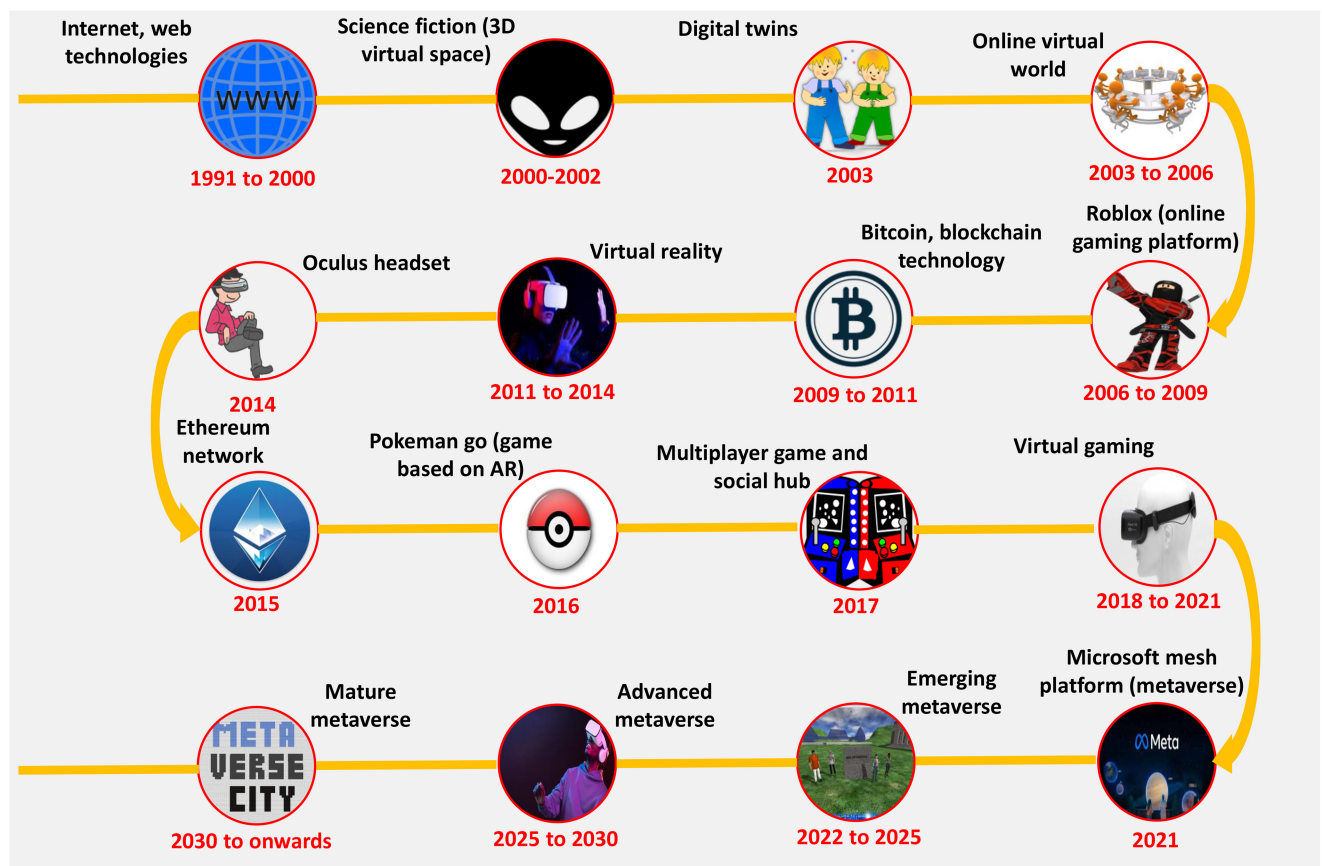


FIGURE 1. An empirical study of the Internet invasion of the metaverse is presented in the timeline revolution in metaverse.

machines to interact with natural language, and the graph below shows the exponential expansion of deep learning transformers [53], [54]. In Figure 3, we show how Growth of Deep Learning Transformers from 2018 to 2021.

The idea of the metaverse has seen a surge in popularity in recent years, emerging closely following the advent of the Internet. Figure 1 illustrates key milestones in the metaverse's evolution, ranging from the seminal development of the Internet in 1991 to the establishment of the first virtual world, Second Life, in 2003. More recently, major technology companies have embarked on notable metaverse initiatives, marking significant strides in this evolving digital

realm. Consider the following transformers: the Generative Pre-trained Transformer (GPT) dealt with 110 million parameters; the newest Google Brain transformer dealt with over 1 trillion parameters. GPT-4 will most likely have far more. This suggests that the volume of DNN networks will continue to grow in the future. With the advancement of neural networks, AI has already achieved a lot of success in voice recognition in Alexa, Tesla's autonomous driving system, Google image recognition, and a few algorithms that elicit reactions from social media and deep fakes; however, all of these applications are just basic in comparison to AI's future applications [53], [55]. The Metaverse is

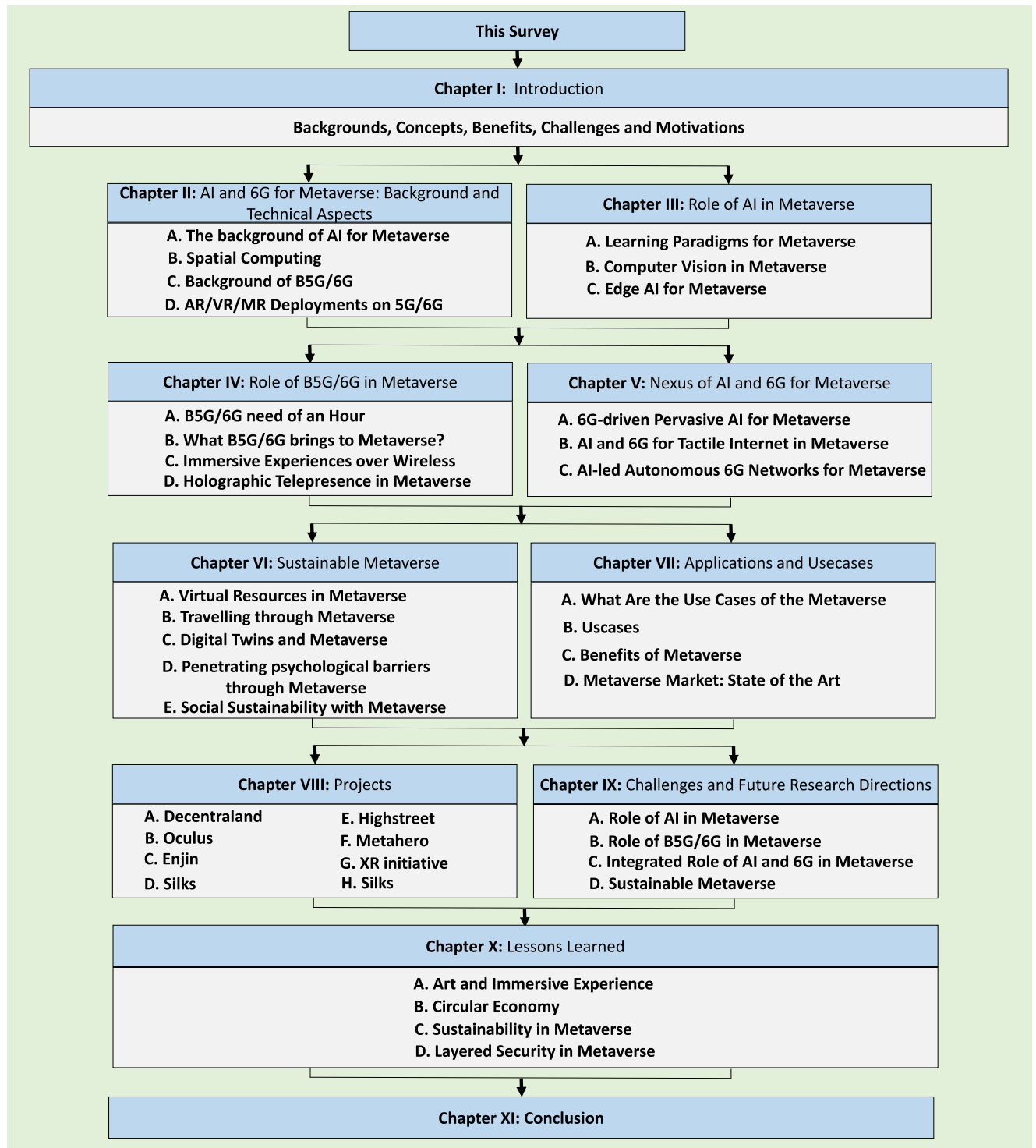


FIGURE 2. Structure of this survey.

not in the future; it is a transformation from being to becoming.

The Metaverse is where the physical and digital worlds intersect; it contains the shared virtual environment, AR glasses, headgear devices, and Oculus VR headsets. These can be accessed over the Internet via smartphones and

wristband technology. People will play, learn, create, shop, and communicate with friends in a virtual, online world. Today, the Metaverse is emerging as metaphysics, or, as we might say, the transformation of the universe. In the past two years, we have seen that with the covid epidemic, digital technologies shift their waves quickly, and it has

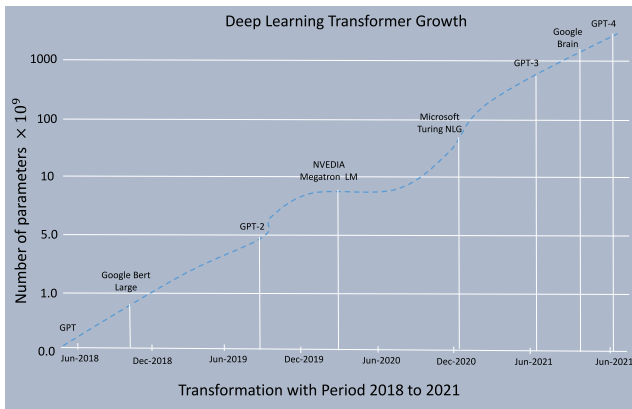


FIGURE 3. Growth of Deep Learning Transformers from 2018 to 2021.

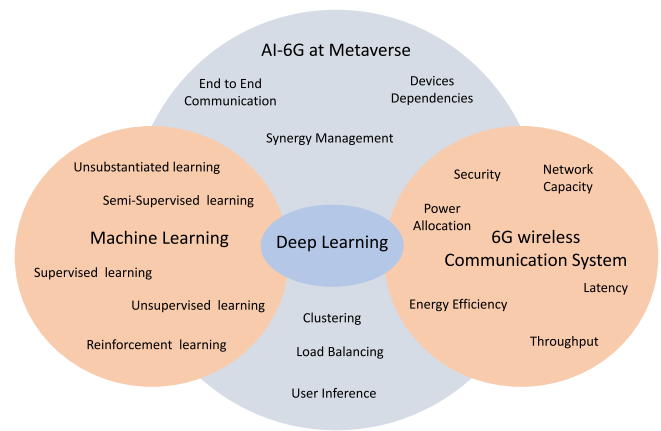


FIGURE 4. Application and infrastructure-level machine learning and deep learning techniques for 6G.

been in the past as well. The 1980s saw the rise of computers, the 1990s saw the rise of the Internet, the 2000s saw the rise of mobile Internet, the 2010s saw the rise of AI/ML/DL/Data analytics [56], and the 2020s saw the rise of true AI/Trans-AI/Meta-AI. The Metaverse, transverse, or omniverse could be the next wave. The waves are now merging, such as the Internet on PCs, the Internet on mobile devices, and AI/ML on the mobile Internet. The Metaverse will demand the Internet, mobile devices, and REAL AI. A Metaverse contains simulated AR, VR, MR [57], [58], [59], [60], [61], [62], [63], a 3D World Wide Web, and other forms of digital twins, including digital humans as intelligent avatars. Metaverse will function as a real-time digital environment containing all feasible entities, occurrences, activities, and interactions. Currently, trillions of dollars are being invested in Metaverse projects like AI-driven digital reality to offer a digital infrastructure that can accommodate all of its social media networks, e-commerce, and big tech oligopoly [64]. We risk creating a Matrix-like Metaverse of digitized humans and superintelligent agents as a virtual world where young people can transcend the meaningless reality of the real world in which they live. The Metaverse is a virtual reality that integrates all essential aspects of cyberspace or the world wide Web, such as cloud and edge computing, social media, online gaming, augmented reality (AR), virtual reality (VR) [57], [58], cryptocurrencies [65], and AI/ML/DL platforms [56] and applications, to allow users to interact virtually. Everything we use anyway, such as video conferencing, games, email, mixed reality, e-commerce, social media, and Netflix/YT live-streaming, are all part of the Metaverse. For many MMOG gamers, the Metaverse, defined as the Internet filled with mixed, virtual, and augmented worlds, is more real than any physical reality. It is as real as its technological solutions, which include social media, virtual world games, extended reality, simulation and modeling, human-computer interaction, digital twin, machine learning and reasoning, data analytics, computer vision, edge and cloud computing, and mobile networks, all of which are powered by true

AI Metaverse technology. Using machine learning and deep learning, we have demonstrated the detailed involvement of the metaverse in 6G technologies in Figure 4.

C. SPATIAL COMPUTING

Spatial computing is the digitalization of machine, human, and object activities and the locations in which they occur to facilitate and improve actions and interactions. Spatial computing is the seamless integration of three technologies: augmented reality (AR), virtual reality (VR), and mixed reality (MR) in a three-dimensional world [66], [67]. This technology can digitally revolutionize how industrial organizations optimize operations for front-line workers in factories, work areas, and logistics. Spatial computing technology is analogous to the commonwealth of the physical and digital worlds. This means that almost all people no longer interact with computers in the fashion that an impartial observer should; conversely, they choose to encounter what it is really like to be in the digital domain by associating with elements that only reside in it. In contrast to traditional computing, which is predominantly two-dimensional, spatial computing allows users to think out of the box and communicate with gadgets from above the screen. The innumerable devices are already on the marketplace for spatial computing. Here are a few examples: VR Headsets, AR Glasses, and Hybrid Gear are all examples of cutting-edge technology [68]. Whereas VR headsets enable visitors to explore being a part of a virtual universe, AR Glasses allow individuals to go greater depth into the digital space, and Hybrid Gear combines VR, AR, and MR technology. Since the user may fully integrate their senses, this program enables them to enjoy a cinematic experience. In the past, gamers adopted VR headsets to interact with video game items and avatars. Their application has recently expanded to encompass additional applications such as training and modeling. AR Glasses are gadgets that project data and visuals and are particularly beneficial in industrial workplaces. Google Glass and Microsoft HoloLens are two special AR

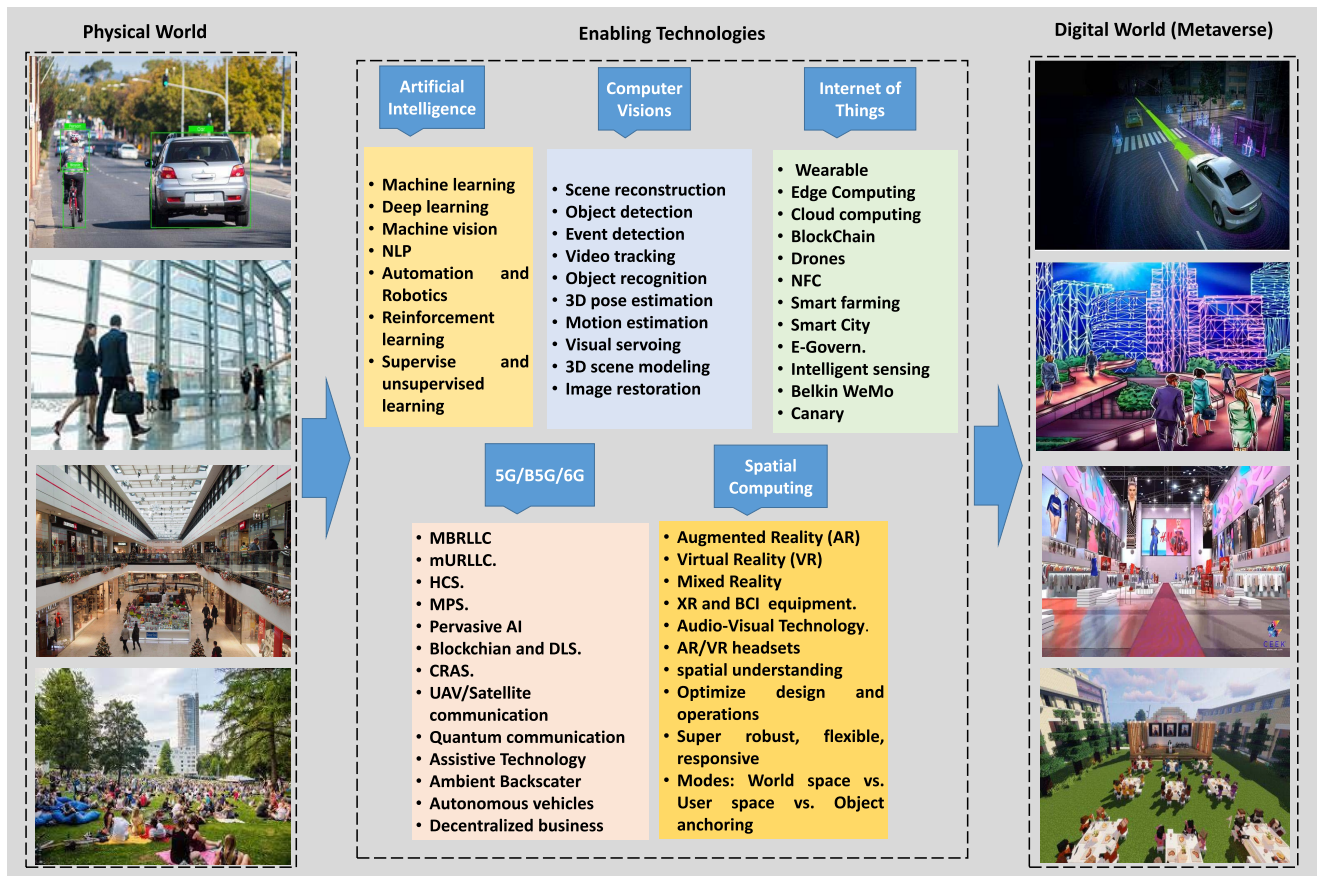


FIGURE 5. Metaverse refers to transformation of physical reality into the digital realm, so it could be a mix of physical reality and digital realm such as AR, VR, and MR.

glasses on the market right now. FellReal's multi-sensory mask is an excellent example of such technology. While such merchandise is still in the works, major tech corporations like Samsung, Google, Apple, and Microsoft invest in startups to create cutting-edge hybrid tools and equipment. By showing how the physical world will be transformed into the digital world via the rise of Metaverse, we demonstrate in Figure 5 how technologies such as enabling technologies will play a significant role. The ultimate advantage of spatial computing is the ability to interact with digital objects. It provides extra privileges that we could only dream of aeons ago but are now a "spatial" reality [69].

1) VIRTUAL REALITY (VR)

Virtual reality is defined as computer technologies to construct space that can be explored in 360° (VR). Unlike traditional technologies, virtual reality (VR) plunges the user in a virtual world to give an interactive experience [70]. It has been revealed that virtual reality has the most conspicuous characteristics of completely synthetic vistas. Commercial VR removes real-world vision and provides video to each eye, allowing for depth of view [71]. It is a virtual environment in which the user is fully immersed and is interacting with real items via interactive techniques via the Internet. This technology is augmented with head and

body tracking to link the virtual environment to the user is viewing. Furthermore, VR is described as the "farthest end from reality in the Reality-Virtuality Horizon" [72]. In a VR environment, users can produce their own content, such as VR painting, to devote their complete attention to the virtual worlds, which are distinct from the real environments [73]. Interacting with virtual entities in a virtual space can assist in discovering user accessibility, such as changing the scene's shape and adding new tasks. The collaboration between multiple users in virtual space can therefore occur in real-time, which aligns with well-defined requirements for virtual environments, including a sense of location, time, and availability, gestures, texts, and voice communication, and information sharing [74]. Furthermore, Virtual Reality expands democratization and permits more humans to engage with digitization. For example, Google's Tilt Brush5 enables customers to create unique artworks using VR goggles. The link between new and classic arts technologies is not unidirectional; instead, they can live harmoniously. When contemplating the Metaverse, users should locate themselves in their own shared spaces while interacting with the physical analogue, such as AR and MR. The goal of the Metaverse is to create multiple shared spaces in which to undertake concurrent activities among existing objects, avatars, and their relationships, for

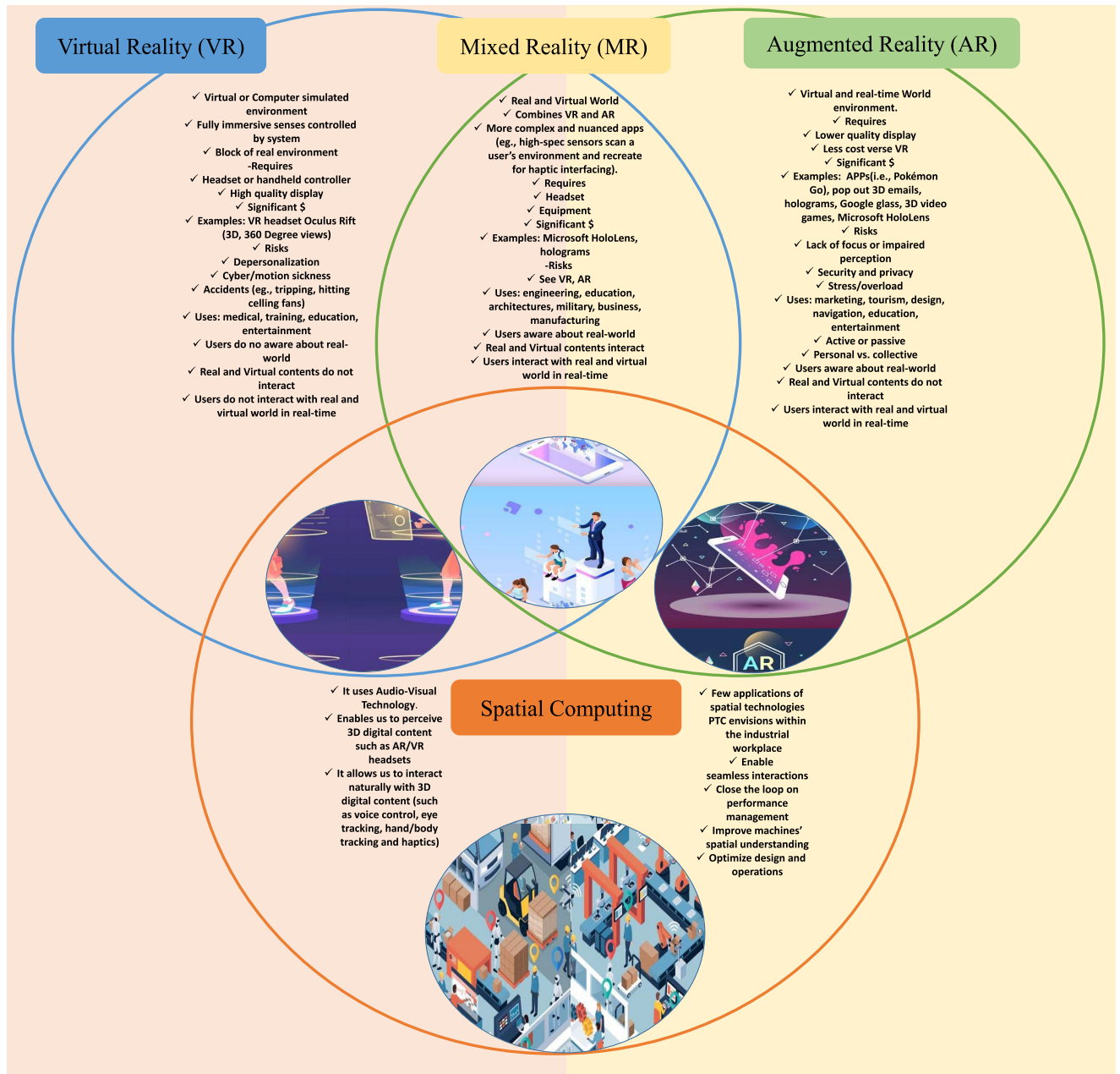


FIGURE 6. Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), explored in depth.

example, Object-to-object, object-to-avatar, and avatar-to-avatar interactions. To represent the events of the virtual spaces, all users who participate in the virtual environment must synchronize [75]. However, synchronizing dynamic events at scale is a large problem because unlimited users can simultaneously together act on virtual objects and interact with one other without reasonable latency, which might be detrimental to users. VR in the Metaverse seems to be a more advancing technology that may be deployed for various purposes, such as classrooms, to help teach a subject or topic by allowing students to ‘experience’ the knowledge.

2) AUGMENTED REALITY (AR)

Digital visual elements, music, or other sensory stimuli are used in augmented reality (AR) to enhance the physical world. Commercial apps and mobile computing companies are embracing it. Augmented reality (AR) goes beyond virtual worlds to improve our physical surroundings through different experiences. Audio, images, taste, and touch are all possible perceptual input channels for computer-generated virtual elements [76], [77], [78]. Digital toppings are projected on top of our physical environments using the first generation of AR system frameworks. Users’ participation with digital entities has been studied extensively in AR so

far. It is worth noting that digital entities are superimposed on top of the user's physical surroundings, allowing users to perform many actions at once, similar to VR. Interactions with such digital entities in AR are difficult and intended to connect people between the physical world and the Metaverse [78]. The majority of science fiction films use urban and peri-urban concepts to present intuitive AR user interfaces [57]. Like, *Voodoo Dolls* offered a freehand technique in which the user can select and work with virtual content using squeeze motions. Later, *HOMER* proposed a method [79] that provides ray-casting from the user's virtual hand, displays item selections, and is finally deceived. Furthermore, AR will play an important part in our daily lives, such as gaming, annotating directions in new regions, and locating objects based on user surroundings [80]. As a result, we can anticipate that the AR in Metaverse will integrate urban environments, and digital entities will appear in visible and tangible ways on top of various physical things in metropolitan places. We can conclude that AR will facilitate communication between the physical and virtual worlds in the Metaverse. However, mapping virtual objects with regard to their corresponding position in the real environment needs a significant amount of effort for simple actions such as detection and tracking [81], [82], [83]. As the first research prototype of augmented reality outdoors, *Traveling Machine* is considered groundbreaking. A head-mounted display containing map navigation information and a GPS device are included in the prototype. Using a pointer and touch surface, users interact with AR maps [84]. A recent AR headset, however, has shown great advancements, particularly in mobility. AR headsets can receive video and auditory feedback, but other senses remain untapped, including smell and haptics [85]. Interestingly, AR headsets are not the only way to view Metaverse content. AR patches, as well as digital entities from the Metaverse, can be supplied via a variety of devices, including but not limited to AR headsets [57], [58], hand-held tablet devices [86], overhead projectors [87], and tabletops [88], Pico (portable) projectors [89], and so on. Matter of fact, in terms of switching user attention and occupying users' hands, AR headsets have an advantage over other tactics. The finest aspect of this technique is that users must shift their focus between physical environments and digital material on other sorts of AR gadgets. AR headsets also allow users to visualize [69], [90], and the user's hands will not be burdened by tangible items functioning as processing elements. These advantages make AR headsets more immersive in the Metaverse via AR lenses. Augmented reality continues to evolve and spread across a wide range of applications.

3) MIXED REALITY (MR)

A mixed reality (MR) environment is one in which physical and digital items coexist and interact in real time in a physical and virtual world. In other words, we can say that MR is a hybrid of AR and VR technologies [91], and we will go over

the role of MR in the Metaverse further. There is no formal definition of MR, but it is imperative to have a name that describes the alternate reality that exists between the two poles of AR and VR. While reading the previous literature, we came across several descriptions of MR, including a "traditional" notion of MR in Continuum [91], MR as a generic term for AR [92], MR as a type of liaison [93], MR as a combo of AR and VR [94], MR as a synchronisation of environments [88], and a "greater" version of AR [95]. MR is a combination of AR and VR that allows users to interact with virtual elements in physical environments, according to the scientific community. Nowadays, mobile AR is the most popular mixed reality service on social media. Mix reality events are created by AR filters on Instagram. Microsoft Windows Mixed Reality combines all user experiences to create holographic portrayals of people, 3D models, and their real environment. In comparison, as seen in existing applications [85], AR typically shows information layered on physical locations without regard for compatibility. Due to the massive aforementioned characteristics of MR, it is regarded a more powerful version of AR, with collective linkages to physical spatial, user interaction, and virtual entities [85], [96], [97], [98]. Humans, computers, and the surroundings can interact naturally and immersively with mixed reality. The world of computer vision, graphics, display technologies, input methods, and cloud computing has changed dramatically. Sensor and processing power breakthroughs are resulting in novel computer perceptions of surroundings based on innovative input modalities. A person's body position in the physical world, objects, surfaces, and boundaries, environmental lighting and sound, object classification, and geographical locations can all be captured via environmental inputs.

D. BACKGROUND OF B5G/6G

To fully utilize the Metaverse, we must have smooth outdoor mobility enabled by cellular networks such as the 5G and 6G networks. With the advent of 6G technology, 5G has been ruled out, but it is still being rolled out to replace the aging 4G standard [99]. As shown in the Table 5 below, we have laid out different ways in which enabling technologies play a key role from 1G to 6G. 6G networks are being developed and are projected to be speedier, with increased capacity and fewer latency [100]. It can be seen that 6G networks will encompass a wide range of capabilities, as well as current mobile applications such as VR/AR, AI, and the IoT. Mobile network operators are also predicted to use flexible distributed approaches for 6G, including local spectrum licensing, bandwidth allocation, and connectivity sharing. Mobile edge computing, short-packet communication, and blockchain technology would be responsible for all of this. As evidence suggests that new wireless technologies are released regularly after every ten years, it may be anticipated that 6 will be in use by 2030. In the future, more designs and protocols will be launched in 6G. Users will continue to use more IoT, mobile devices, and similarly use a lot of

TABLE 5. Role of key enabling technologies from Pre-4G to 6G.

Generations	Pre 4G	4G	5G	6G
Advantages	• Improve voice clarity • The network uses the analog signal (1G) • Consume less battery power • Data and voice signals are digitally encrypted • Fixed and variable data rates • Asymmetric data rates (3G)	• High speed • Tight network security • High usability: anytime, anywhere and any with technology • Support for multimedia services low transmission cost • Low cost per bit	• Greater speed in the transmissions • A lower latency • Greater capacity of remote execution • A greater number of connected devices • Possibility of implementing virtual networks • Your PCs can be controlled by handsets	• AI-assisted intelligent connectivity • Depth connection • The term "holographic connection" refers to the use of AR/VR to provide continuous coverage anywhere • A ubiquitous connection that spans space, air, ground, and sea • By removing time, space and workflow barriers, 6G will transform the health-care industry
Disadvantages	• Poor voice quality • Large phone size • Poor battery life • Complex data, such as videos, could not be handled by the system • Different handsets are required • Too little bandwidth • Consumption of energy is high • Spectrum license cost • High expenses of 3G phones • 3G compatible handset • Connection rate	• The battery uses is more • Hard to implement • Need completed hardware • It required the use of 4G technology • It is still costly to build a next-generation network • The network has more problems has security issues	• Old devices are unable to handle 5G, so they must be replaced by new ones • A costly process • Developing infrastructure requires a high price tag • There is yet to be a resolution to the privacy and security issues	• Multi-connection architecture and cell-less architecture are used in 6G. In a cell-less deployment, UEs are not connected to a single cell, but to the RAN. Network architecture needs to be redesigned • As part of its communication, 6G uses visible light frequencies; therefore, its drawbacks could be considered to be those of 6G wireless technology • It is challenging to design communication protocol stacks for network and terminal types of equipment
Applications	• Voice calling • SMS	• HD movies • Video conferences • Telephony • IoT, Wearable, Smart manufacturing • Edge computing, Smart farming, AI	• Assistive Technology • Immersive AR/VR, Advanced AI • Autonomous vehicles, Decentralized business • A greater number of connected devices • 6G has a high data rate (Tb/sec) and a short latency (sub-ms).	• AI-assisted intelligent connectivity • Depth connection • The term "holographic connection" refers to the use of AR/VR to provide continuous coverage anywhere • A ubiquitous connection that spans space, air, ground, and sea • By removing time, space and workflow barriers, 6G will transform the health-care industry
Application				
Types	• Text messages, Picture messages and MMS • Wireless voice telephony, Mobile Internet access, Fixed wireless • Internet access, Video calls, Mobile TV	• Amended mobile web access, IP telephony, Gaming Services • Video conferences • High definition mobile TV, Video conferencing, 3D television	• eMBB • uRLLC • mMTC	• MBRLLC • mURLLC • HCS • MPS
Application Types	• Text messages, Picture messages and MMS • Wireless voice telephony, Mobile Internet access, Fixed wireless • Internet access, Video calls, Mobile TV	• Amended mobile web access, IP telephony, Gaming Services • Video conferences • High definition mobile TV, Video conferencing, 3D television	• eMBB • uRLLC • mMTC	• MBRLLC • mURLLC • HCS • MPS
Device Types	• FDMA • TDMA • CDMA • W-CDMA • GSM, EDGE, UMTS, DECT • WiMax, CDMA 2000	• ADVANCED LTE, WirelessMAN-Advanced, IEEE 802.16m, Three-GPP Long Term Evolutions • WiMAX (IEEE 802.16e) for mobile devices • China's TD-LTE network • The UMB (formerly the EV-DO Rev. C) • Flash-OFDM	• Smartphones • Sensors • Drones	• MBRLLC • Sensors and DLT devices CRAS • XR and BCI equipment • Smart implants
Rate Requirements	2.4 Kbps to 2 Mbps	33.88 Mbps	40 to 1100 Mbps	Up to 1 Tbps
Rate End-to-End Delay Requirement	20 to 100 ms	10 ms	5 ms	< 1 ms
Rate Processing Delay	100-1000 ms	20-30 ms	100 ns	10 ns
Architecture	Wide Area Network	Hybrid Network	• Denser sub 6 GHz small cells with umbrella macro base stations • < 100 m tiny and dense mmWave cells	• High-frequency cell-free smart surfaces powered by mmWave tiny cells that can be accessed by mobile and fixed devices

data at increasing rates as 6G evolves, indicating the more theoretical aspects of 6G are predicted to emerge [30], [38].

1) 5G EVOLUTION

Although 6G is replacing 5G [101], however, 5G technologies are still required. Wireless telecommunication industries continue to rely on 4G for consumer use, and 5G is attempting to replace the outdated technology, albeit gradually, with most deployments taking place in tightly populated regions. In 2009, the 4G/LTE [102] standard was introduced, which proved to be a game-changer for mobile devices by increasing data speed and letting users watch HD

movies, play online games, and exchange enormous amounts of data at speeds of up to 33 Mbps. 5G [101] outperforms 4G by using microwave and mmWave technology to boost its speed to roughly 900 Mbps or more. Faster speeds and capacity are comparable to commercial broadband providers, offering more uses beyond streaming media. IoT and edge computing will have real-time sensing capabilities, which means they will obtain data instantaneously by leveraging the cloud. In the healthcare profession, such as medical services, instantaneous knowledge from patients is required for diagnosis and treatment, which can only be accomplished with faster computations; therefore, 5G has applications in

retail and industry. The list is virtually endless, but we will not see 5G's entire potential until the advanced technology is implemented globally.

2) 6G AND INTERNET OF EVERYTHING

As already mentioned, 6G [100] is still in development and is too early to have accurate information on its technology or functionality. We anticipate that the telecommunications industry will use dynamic, decentralized marketing strategies with local spectrum licensing/sharing and infrastructure sharing in 5G. 6G is fully integrated with Internet-based systems that enable speedy communication between users, gadgets, automobiles and the surrounding environment [103]. As a result, it is possible to estimate when we will transition from the Internet of Things (IoT) to the Internet of Everything (IoET), which 6G could theoretically deliver. The existing fibers can provide up to 1 Gbps; however, the researchers believe that a 6G network could provide thousands of times quicker than optical fibres. The Federal Communications Commission (FCC) has opened the door to 6G speeds in 2019, enabling firms to experiment with terahertz waves in the 95-GHz to 3 THz spectrum. 5G, on the other hand, uses a low band as low as 24 GHz to 40 GHz, such as mmWave and microwave technology. Although terahertz waves could enhance 6G speeds to 1 Tbps, they would be subject to the same restrictions as 5G. Using N-Polar gallium nitride high-electron-mobility transistors (HEMTs), researchers from the University of California, Santa Barbara have created a device to speed up the 6G development process. These HEMTs feature a junction between two materials with differing bandgaps that work as a channel instead of the common doped region found in MOSFETS, allowing the device to operate at significantly higher frequencies (140 to 230 THz), as required by 6G [104]. As time passes, new advancements in 6G emerge. Last year, researchers from Singapore's Nanyang Technological University and Japan's Osaka University produced a device for terahertz waves that could be used for 6G [105]. Engineers designed millimeter wave products for G-bands that function in terahertz waves this year. A few tools can help 6G become a reality and progress beyond the research phase. It may take the time that 6G becomes increasingly widespread in real-time applications to roll out 5G progressively.

E. AR/VR/MR DEPLOYMENTS ON 5G/6G NETWORKS

Although AR/VR technology has existed for a couple of years, its scale adoption depends on 5G/6G technology and edge computing. In order to enable the use cases, 5G/6G must bring ultra-low latency and high bandwidth. As a result of private 5G/6G solutions, many industrial and enterprise customers can carry out mission-critical processes with the capabilities necessary to accomplish this. While public 5G/6G networks do not extend adequate coverage, do not deliver a particular ability to the required level, or are deemed to be unreliable, private 5G/6G networks provide the capabilities required for mission-critical applications.

The metaverse proves to have huge potential when it comes to securing the AR/VR/MR space in the future. It is designed to allow its users to build a full-featured virtual world governed by a set of rules without the involvement of platform developers or the risk of being exposed to their risks. The second benefit of BC is that it allows copyright protection to be applied to the content as a user may record it. Finally, BC can enhance the popularity of VR by merging the market for cryptocurrencies with VR, resulting in increased profitability due to the merger. There are several aspects of AR/VR/MR that could benefit from the use of 6G that are outlined below.

- With the advent of 6G networks, it is possible to communicate at THz in the submillimetre range with extremely low latency. As part of 6G, virtualized service sets simplify holographic communication over physical boundaries and enhance management capabilities. As a result, 3D imagery can be experienced in real-time (XR) in conjunction with autonomous driving, etc.
- For data security in AR/VR applications, it is essential to ensure trusted decentralization among multiple nodes to ensure massive data-sharing.
- The fast display and processing of images and videos required by AR/VR assets requires that the data be stored and exchanged through a local central server due to the amount of memory and processing required limitations.
- Since AR/VR-oriented applications AR [92], [94], [95] consume a great deal of data and bandwidth; the central server could become overloaded due to multiple asynchronous communications among the AR/VR devices.
- For military and battlefield applications that use AR/VR devices, Blockchain improves cybersecurity through sharing sensitive data, law enforcement, and public safety.
- By creating a user-defined marketplace for storing and uploading AR content, Metaverse can assist in the commercialization of AR devices.
- In addition to assisting users and developers in downloading and uploading content, communication can also facilitate the development of new applications and set up marketplaces and storefronts for AR/VR/MR devices to make them more commercially viable.

A summary of recent papers incorporating AR/VR/MR [92], [94], [95] into 5G/6G networks can be found in the Table 6. The adoption of AR and VR at scale has yet to become mainstream. 5G and edge computing can now overcome some of these challenges. We explore specific use cases and real-life applications in Section VII.

III. ROLE OF AI IN METAVERSE

In this section, we present the AI pyramid for Metaverse technology, followed by methods related to different learning paradigms, computer vision, and Edge AI. This subsection also serves as a basis for discussing sustainable metaverse in Section VI. Post Facebook's name change

TABLE 6. State-of-the-art on AR/VR/MR implementations in various industry verticals envisioned by 5G and 6G technology.

Reference	Years	Aims and Objectives	Contribution	Limitation	Taxonomy Parameters
[106]	2019	IoT and AR/VR are being used in modern industries to demonstrate how they can survive	Analyze the benefits and challenges of integrating AR with blockchain.	A hypothetical scenario is considered rather than a reality scenario	BC based AR/VR/MR
[107]	2020	Observing how VR, AR, and AR have been integrated to benefit companies and industries.	The system has the potential to eliminate the need for third parties.	There are limited use cases in the scenario	BC based AR/VR/MR
[108]	2020	To see how blockchain can be integrated with mobile devices and AR/VR	The efficiency of VR combined with blockchain technology and augmented reality	AR is not taken into account	BC based AR/VR/MR
[109]	2020	An observation of blockchain's convergence with 5G and 6G networks for the development of immutable, distributed and smart applications	Practical overview and solution of AR/VR	Does not address existing problems with 5G networks	5G/6G enabled AR/VR/MR
[110]	2020	5G network problems countered by AI	Taxonomy for 5G networks at a high level	AI and 5G problems are not discussed	5G/6G enabled AR/VR/MR
[111]	2020	Demonstration of authentication and key protocols for 5G and 6G networks	In blockchain applications, various states are observed in various situations	Threats to security are not discussed	5G/6G enabled AR/VR/MR
[38]	2022	A metaverse system based on 6G edge intelligence was investigated	The organic integration of edge AI and metaverse enabled by 6G	Edge node computing power distribution is imbalanced.	5G/6G enabled AR/VR/MR
[1]	2022	A metaverse vision towards enabling 6G wireless development is presented	Identifying key enablers, such as interactive experience technologies, avatars, and digital twins and their potential benefits for wireless systems and mobile services	Wireless systems that self-configure only	6G enabled AR/VR/MR

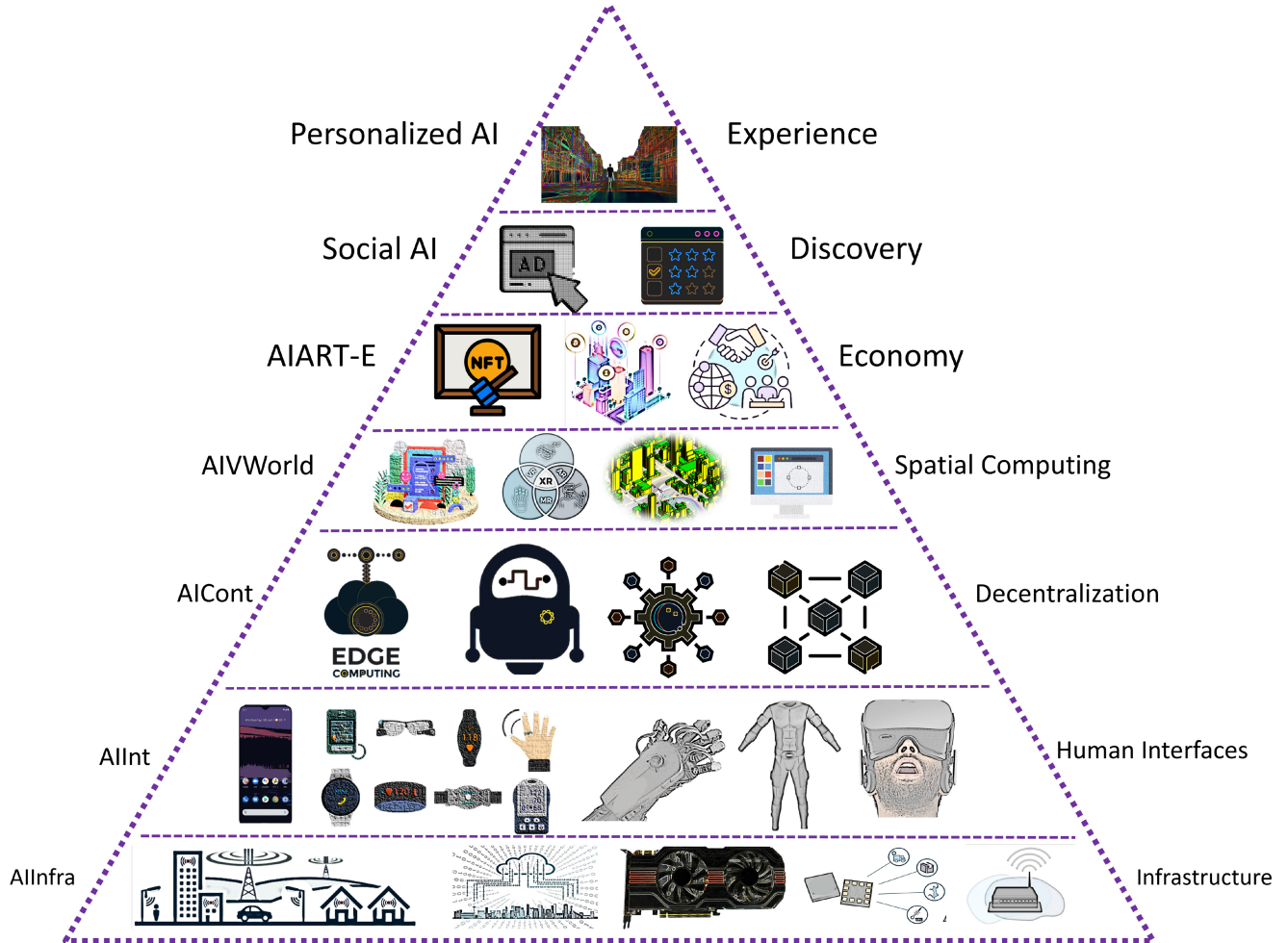


FIGURE 7. Layered Architecture of Metaverse by Jon Radoff. The labels on the right side are original layers defined in “Building the Metaverse”, while the labels on the left side exhibit equivalent mapping in the context of AI.

to Meta, the rejuvenation of the Metaverse field has been the talk of the research community. Another reason for inclined interest towards the Metaverse is its impact on socioeconomic and technological aspects, such as combining 3D animation, virtual reality, blockchain, non-fungible tokens, digital economy, and many others. The non-fungible tokens (NFTs) created a lot of hype that explained the role of blockchain in the context of the Metaverse, however, this section will mainly focus on the role of AI in the said technology. Recently, an article was surfaced, which explained the concept of the Metaverse in the context of

value chain.⁸ The article summarized the Metaverse as the (real-time activity-based Internet) and proposed an abstract layered architecture for the same. We use the seven-layered Metaverse architecture as a reference to explain the role of AI, as shown in Figure 7. We briefly explain the areas and define the equivalent AI mapped role in the layered schema to understand the diversity and advancements that AI brings to the field of Metaverse. This correspondent has already

8. <https://medium.com/building-the-Metaverse/the-Metaverse-and-artificial-intelligence-ai-577343895411>

been performed by David Pereira,⁹ but this study further elaborates on the use of AI in each layer, accordingly. We explain each of the corresponding layers in a bottom-up approach.

AIInfra: It is apparent that with increasing popularity, a large number of users will opt to use the services associated with Metaverse. In this regard, the infrastructure should be capable of accommodating massive machine-type communication (mMTC) devices along with the support for executing AI-based models. Furthermore, it should be noted that the infrastructure is the base for the services being offered at stacked layers, therefore, the support for temporary storage of data or support for cloud connectivity is also necessary. For instance, 5G/6G networks already allow support for AI devices and operations. Similarly, Microelectromechanical (MEMs) devices enable the wearables to perform automatic sensing and data collection, and Graphic Processing Units (GPUs) enable the device to perform faster computations. Currently, there are many plug-n-play solutions available for making backward devices compatible with the newer ones. Application program interfaces (APIs) and software packages allow passive hardware to work as active ones. For some applications, it is the software only that is needed to obtain the desired results. Therefore, AI-devices AI-based devices refer to both hardware and software, respectively. Together, the AI-based devices provides the necessary infrastructure to perform decision-level operations and allow the Metaverse services to operate in a seamless manner, hence the name, AI-based Infrastructure (AIInfra).

AIInt: Metaverse services heavily rely on user experiences and, to make them satisfactory, design of user interface is the initial step. Although the design of interactive and intuitive user interfaces helps improve social interactions, it can be a hindrance to some of the users that include disabled, introvert, and specially challenged people. To make the interface accessible in general, AI methods can be extensively used (AIInt). For instance, usage of computer vision approaches for visually challenged users, or generating automated voice from text for visually impaired ones, design of social avatars for friendly interaction in virtual world, brain computer interface for specially challenged users, and so forth. AI-based methods can not only be used for enabling the user-experience in terms of interface design for some users, but also can be used to improve the accessibility and interaction with the interfaces, in general. As the users interact with the devices in AIInfra through the interface, AIInt becomes their main impression. Users, especially in Metaverse, would not like to be frustrated with badly or complex designed interfaces. As the applications in Metaverse will increase, they will strive for the users' time and AIInt would be one of the reasons for either churning in or out of the application. A recent survey from Localytics¹⁰

indicates that 71% of the users churn out before 3 months if the interface is not user friendly and upto their expectations.

AICont: Decentralization has been extensively achieved through smart contracts and blockchain based methods, however, Metaverse emphasizes on democratization along with the decentralization. Decentralization allows users and creators to protect ownership and exchange entitlements and assets easily in the digital space; however, it does not ensure disintermediation from corporations, financial institutions, and investors. For instance, let us consider the Adidas NFT case, which was dropped in December 2021 with a constraint that purchases were limited to 2 persons. The NFT was sold out in less than 1 second because a single user purchased 330 of them in a single transaction. This was accomplished by modifying smart contracts, which proves that the democratization cannot be achieved by just using conventional contracts. Democratization refers to the equal opportunity for all users, thus snatching away the power from big corporations. In this regard, AI can be used to detect modifications and anomalies concerning smart contracts, hence the name AI-based smart contracts (AICont). Furthermore, AICont can leverage the information acquired from AIInt and infrastructure to detect non-democratic activities for preventing such kind of incidents in blockchain transactions.

AIVWorld: The creation of virtual environments is of vital importance in Metaverse, and making it believably realistic is one of the research challenges to solve. Some examples of digital worlds are NVIDIA's Omniverse¹¹ and Spatial IO.¹² These platforms provide a set of components to simulate the real-world objects and create unique digital worlds in quite an impressive manner. The use of AI is extensive in creating this set of components as the process needs to be autonomous, realistic, and visually pleasing (AIVWorld). These virtual worlds can be used for variety of applications such as building massive worlds, creating simulation environments for robots and autonomous vehicles, simulating voice-based commands in the digital world, and so forth. AI will be responsible for not only creating realistic digital worlds, but also testing automation within the Metaverse. Some snapshots from Spatial IO virtual environment are shown in Figure 8.¹³

AIART-E: Non-fungible tokens (NFTs) have proven to be a stepping stone in Metaverse from an economic perspective. It is the empowerment of artists and non-artists alike. The artists might use the platform to broaden their horizon and appeal while the non-artists may use it to learn new skills or adding diversity to their portfolio. For non-artists, AI can be used to generate unique art as well. Considering the expansion of AI usage among noncoders (thanks to GPT-3 and similar models), the users will be able to generate their own NFTs. The advances in natural language processing

9. <https://towardsdatascience.com/how-ai-will-shape-the-Metaverse-4ea7ae20c99>

10. <http://info.localytics.com/blog/mobile-apps-whats-a-good-retention-rate>

11. <https://developer.nvidia.com/nvidia-omniverse-platform>

12. <https://spatial.io>

13. <https://spatial.io/>



FIGURE 8. AI in Avatar and Environment Design for Metaverse: Image courtesy: <https://spatial.io/>.

(NLP) have allowed AI to generate art for economic enrichment (AIART-E) in the digital space. Unique stories can be generated using models such as GPT-3 [112], [113], while realistic unique art can be generated from a single line of text using DALL-E [114], [115] and GauGAN2 [116]. There are also community-driven platforms governed by autonomous artists that build algorithms to create arts. One of such community-driven platforms is Botto.¹⁴ Some creations from Botto, GauGAN2, and DALL-E are shown in Figure 9.¹⁵ [114], [116] The use of AIART-E provides an economic sustainability by creating circular economy ecosystem.

14. <https://botto.com/>

15. <https://botto.com/>

SocialAI: The core motivation behind Metaverse is to create an interactive environment that improves the social network experience. However, with current social networking platforms, there is a lot of abuse, hate, and serious concerns in terms of safety and inclusion for children and minorities. Such constraints can contribute to the depowering of digital personalization and self-knowledge, which are the things that Metaverse stands for. The use of artificial intelligence can be leveraged to improve the experience of social networks (social AI). The techniques can be used for the machine learning observability, focus more on Explainable AI that can avoid bias, compute content relevance with respect to the minority groups belonging to different ethnicity, culture, geography and language, and detect hate and abusive speech.



FIGURE 9. Images generated with Botto, GauGAN2 and DALL-E.

PersonalizedAI: The final layer in Metaverse pyramid is the hyper-personalization in terms of experience. In terms of AI usage, the former layers leverage the techniques to achieve goals that ultimately contribute to enhance the user's performance. However, the experience enhancement was applied in a general manner. In this layer, the goal is to provide the user with a personalized experience that is specific to each user in the Metaverse. For instance, adjust the gaming models with respect to users' emotions or mental well-being, or apply personalization by considering the users' disabilities. Personalized AI can be explored in different ways for a variety of applications such as education, healthcare, gaming, socialization, sports, and others using real-time analytics.

A. LEARNING PARADIGMS FOR METAVERSE

Over the years, applications in Metaverse such as robotics, embodiment, virtual reality, augmented reality, digital rendering, and more saw remarkable progress through supervised learning techniques [117]. However, the supervised learning strategy tends to make the Metaverse application task dependent, as it is highly based on human supervision. Although, diversified learning strategies such as reinforcement learning [118], self-supervised learning [26], and more have been proposed to make the Metaverse application task independent, its still a work in progress. The Meta AI research group is exploring the self-supervised paradigm, specifically in the domain of text and speech, to make advances in task-independent learning networks. Recently, Meta AI research released the data2vec model which is presented as a unified solution for the speech, vision, and natural language processing task while leveraging multiple modalities [119]. Currently, Meta AI is working towards more unified models that could leverage multiple modalities while helping in reading lips and understanding the speech

semantics to make leaps of progress in digital reality. While Meta is exploring the self-supervised paradigm, its rival Google's DeepMind has stuck with supervised learning and uses massive amounts of data from VRChat to train a digital agent on how to interact with humans in a simplified environment. In 2018 alone, 16 million hours of VR data was generated. Google DeepMind used 20,000 hours of VRChat data to train a digital agent to learn ground language while interacting with humans.¹⁶ The study showed that the digital agent becomes curious and autonomous with such a training strategy. According to the experiments, the DeepMind suggested that it could pave the way for understanding how the Metaverse could be equipped with life like intelligence.

B. COMPUTER VISION FOR METAVERSE

In the field of computer vision, Metaverse has gained the most progress, as researchers can replicate human-like avatars or holographic images of loved ones in the digital world. William Shatner who played Captain James T. Kirk of the starship Enterprise in vintage star trek television series is one of the most beloved actors. An AI startup StoryFile¹⁷ acquired hours of William Shatner's footage while answering questions using volumetric cameras. The footage was acquired with a green screen so that William Shatner's image can be easily segmented, and a proprietary model Conversa was used to associate answers with the asked questions. Currently, the startup built a lifelike videobot of the aforementioned actor. Although, the startup used green screen, there are many deep learning based semantic segmentation methods that does not need a green screen to get a person segmented in even a complex scene, such

16. <https://www.youtube.com/watch?v=b-fvsi9YIP4>

17. <https://storyfile.com>

as FCN [120], UPerNet [121], BiSeNet [122], FPN [123], SFNet [124], SegFormer [125], FaPN [126], CondNet [127], and Lawin [128].

There are further many projects in development that can be considered as a technological leap towards Metaverse. For instance, companies are working on the hologram of holocaust survivors. It is an innovative medium to keep stories from the past alive using artificial intelligence.¹⁸ A socially distant santaclaus¹⁹ and avatars of the loved ones. Recently, Microsoft [129] registered a patent for an AI system that could help an individual interact with a dead loved one through its 3D digital version. Similarly, Replika AI²⁰ is also trying to address mental well-being and loneliness through a digital avatar. Apart from people, researchers are also trying to build a digital system for animals. Researchers from Ubisoft china have proposed a rendering keyframe animation method, i.e., ZooBuilder [130] for animals by using OpenPose method [131] for extracting 2D joint coordinates and 2D-3D human pose estimator [132] to track the temporal relationships between connected joints. With the emergence of Metaverse, many Internet-based tools now use computer vision techniques to provide animated 3D human models or realistic animated faces, some of them include Kinetix,²¹ Mixamo²² and StyleGAN2 [133].

One of the developments that is specific to the integration of computer vision and Metaverse is the design and development of 3D spaces and virtual worlds. 3D spaces in Metaverse refers to the rendering and modeling process to create virtual environment. The 3D spaces where users can interact with virtual objects and each other in a 3D environment both in static and immersive manner. The developers and designers used the tools to not only create environments but provide a way to sustain the Metaverse. These tools include but not limited to Decentraland, Open Metaverse Interoperability Group (OMIG), Blender, WebXR Device API, Webaverse, XREngine, JanusWeb, and HyperCube. The 3D spaces have variety of applications that include social interaction, training, education, and gaming. An example of the 3D spaces and virtual worlds is shown in Figure 7.

Seamingly, researchers are also trying to figure out an optimized way of creating 3D spaces in the Metaverse. For instance, Lo and Tsai [134] proposed the use of a virtual reality architecture (VRAM) to enhance the human cognition using cognitive theory of multimedia learning. Their experimental study revealed that the learning process using VRAM is significantly faster in comparison to existing studies. Gao and Yang [135] took a different approach by using collision detection algorithm and the interpenetration of the objects and human body in the virtual world to

optimize the placement of buildings and their interaction. The authors suggested that the realism of their proposed work is superior than the existing methods. Zhao et al. [136] proposed a framework that highlights the visual elements for not only fuel the visual exploration and construction in the Metaverse but also improve its realism from user perspective. They proposed methods and techniques in three phases to improve the graphics content and visual construction pipeline in the Metaverse. The method also provides details on physics-based animation and geometric modeling to design and development 3D spaces. Wang et al. [137] also proposed the framework for creating 3D spaces in Metaverse using macro perspective and human computer interaction theories to improve the user experience. The technical framework and its performance was compared in this study with their existing counterparts to evaluate the efficacy of user experience in the Metaverse. As the Metaverse is currently being implemented by tech giants and is in process of integrating with daily human lives, more sophisticated methods, tools, and frameworks are being developed to improve the 3D spaces in Metaverse as well as improving the user experiences for interacting with the elements designed in 3D spaces, accordingly.

C. OBJECT GENERATION IN METAVERSE

Although Metaverse is a broad concept but to many, its socializing and performing activities within the digital space. Imagine if that digital space is an empty space, who would like to interact and socialize in it? The concept of object generation is quite crucial to the environments in Metaverse as it creates basis for the users to interact and hang out in that digital space. Metaverse needs 3D objects and assets both in terms of diversity and quantity. For instance, for a particular meeting, contemplation, gaming or work, the Metaverse requires wide variety of environments, buildings, and objects to be created. Furthermore, the design of the aforementioned entities also require customization to be different and enhance the immersive experience. However, creating such 3D assets and objects are time-consuming and costly for the developers, 3D designers, and artists. In addition, they have to put a lot of efforts to add variations in terms of textures and geometry for perceiving it to be of high-quality. It will be a continuous process for the Metaverse as it is a content-hungry platform, therefore, the developers, 3D designers, and artists will have to exhaust themselves or an army like workforce will be needed for the generation of such content.

Generative AI technologies can help in not only solving the aforementioned issue but also accompany the artists and 3D designers to boost their productivity. Over the years, researchers have progressed in developing generative models that could leverage the existing data distribution including faces, objects, and text. Generative models can also be termed as distribution transformers as they leverage the prior distribution to sample and transform the modality to

18. <https://www.cbsnews.com/news/artificial-intelligence-holocaust-remembrance-60-minutes-2020-04-03/>

19. <https://edition.cnn.com/2020/12/15/health/children-social-distance-with-santa-wellness/index.html>

20. <https://replika.ai>

21. <https://www.kinetix.tech/>

22. <https://www.mixamo.com/>

target distribution. A sample workflow for generating faces is defined as follows:

- Use multivariate normal distribution to sample random vectors.
- Train the discriminator network to recognize real and fake faces.
- Train the generator network to transform prior normal distribution to image distribution representing 2D images (faces).
- Input the resultant images from generator network to discriminator for verifying whether the generator network generates real or fake faces.
- If discriminator network identifies the input as fake, repeat the training step until the input is identified as real.

In order for the above steps to work properly, it requires a lot of data from the target distribution, computing platform (GPUs) to train, and a lot of training time, respectively. Even though, there are some constraints but the diffusion and generative adversarial networks (GANs) have shown to be exceptional in generating data. Recently, StyleGAN [133] was proposed for image to image translation applications. A recent study has leveraged the StyleGAN to generate high fidelity human faces without acquiring additional facial data [138]. It is also one of the examples where transfer learning can help in leveraging existing pre-trained network to be used for personalized applications.

The objects and virtual entities can now also be generated through text description, thanks to recent Dall-E_2 [115] and Google's Imagen [139]. It is astonishing and quite helpful for Metaverse environment as it uses natural language to generate the images, which is a natural way of interacting among humans and describing any object. Furthermore, it can also help in creating diversifying and personalized content specific to each user while the user interacts with natural language.

The above-mentioned methods can create 2D images with the text description but it is not enough for the Metaverse as the user will interact with the objects and will perceive them in 3D environments. Therefore, the object generation needs to be performed in 3D as well. In this regard, a recent breakthrough has been achieved by NVIDIA with their instance neural radiance fields (Instant NERF) method [140] that undertakes some 2D images from different camera angles and generates a 3D scene. Once generated, the rendering of object in 3D can be performed instantly with respect to the camera motion and viewing. With such progression in generative networks, the content creators and 3D designers will be able to create 3D objects quite easily in the Metaverse, especially for virtual universes or games where the environment requires a certain level of realism.

D. EDGE AI FOR METAVERSE

The use of Edge AI would be quite crucial for realizing Metaverse, as it is highly dependent on low latency and

high throughput to meet the needs of user experience. The fifth generation (5G) networks meet the user experience demands to some extent, i.e., maximum data rate of 10 Gbps and delay of less than 10 milliseconds, but as per the estimations and forecasts, the delay needs to be lower and the peak data rate needs to be higher in order to sustain user experiences in Metaverse. Thanks to the use of AI techniques in combination with edge computing, the foundation to develop emerging mission-critical applications is laid [141]. Several deep learning, soft computing, and machine learning techniques have been proposed to achieve uRLLC, be it active user detection [142], resource allocation [143], scheduling problems [144], and power-management problems [21], accordingly. Recently, AI has also been exploited for mobility prediction, traffic estimation, channel prediction, and spectrum management for maintaining uRLLC. For instance, SCGNet [145] and MCNet [146] were introduced to enhance the spectrum utilization efficiency while demodulating the receiver's signal accurately. In [147] a combination of CNN and LSTM was introduced to predict the channel state information for improving robustness in practical 5G systems. The study [148] proposed a 3D convolutional networks for forecasting cellular traffic by leverage long and short term spatial patterns from the traffic data. In summary, Edge AI techniques are very crucial in achieving low latency with high throughput that acts like a support system for high class integrated services in Metaverse.

E. 6G: A REQUIREMENT FOR AI-BASED METAVERSE

The services associated with Metaverse rendered by AI require the infrastructure to be scalable, services to be lightning fast which require low latency, reliability through stable connection, and security. Although the current generation of communication system, i.e., LTE and 5G, provide some of the basis to realize Metaverse its still far away from large-scale implementation due to the aforementioned characteristics. Since the metaverse needs to support at least thousands if not millions of remote devices that need to process and transmit huge amounts of data, the latency will be the core issue for current network environment as it is considered to be the bottleneck for adaptation of wide array of applications [149]. Some haptic and spatial AI applications require latency of less than 1ms while the transfer rate of more than 1 Mbps [142]. The fifth generation communication system alleviate this problem to some extent but as the Metaverse grows, which is assumed to be the case, a stable and faster new generation of mobile communication will be definitely required [150].

As discussed in previous subsections, large language models will play a key role in understanding user preferences and generating customized and unique environments. In this regard, the training of such models require computing power and a stable connection [151]. However, researchers have shown that the current iteration of network environment is not suitable for training large language models, rather it

TABLE 7. Delays and bandwidth requirement for each of the layer in Metaverse pyramid.

Layer	Delay (ms)	AIT (ms)	AIT-EUE (ms)	TBR	TBR-C
AIINFRA	1.167	2.86	-	-	-
AIINT	3.5	3500	5800	1062 Gbps	530 Mbps
AICONT	500	4500	-	500 Kbps	500 Kbps
AIVWORLD	3.5	8000	19300	63.70 Gbps	210 Mbps
AIART-E	3.5	10000	24400	10.62 Gbps	35 Mbps
SocialAI	1.167	1.25 (Text) / 2000 (Image)	1.37 (Text) / 3400 (Image)	500 Kbps	128 Kbps
PersonalizedAI	150	19200	48800	238.89 Gbps	796 Mbps

works better with small-scale ones, and one of the reasons for such failure is the lack of stable connection [152]. Therefore, in order to realize the metaverse with its full potential, the communication network needs to play an effective part along with the AI methods, respectively.

We analyzed several studies [150], [153], [154], [155], [156] for requirement gathering concerning delays and bandwidth with respect to each layer in Metaverse pyramid shown in 7 and report the figures in 7. The requirement is gathered with respect to delay, average inference time (AIT), average inference time with enhanced user experience (AIT-EUE), transmission bit rate (TBR), and transmission bit rate with compression (TBR-C), respectively. The AIT-EUE refers to the data enhancement techniques for enhancing user experience, for instance, image denoising, image super resolution, and more. The AIT-EUE mainly depends upon the image resolution (assuming that Metaverse mainly deals with imaging technologies). The relationship with the inference time is simple, higher the resolution, higher the inference time. The reported values are in terms of average and also hypothetical, as Metaverse and 6G are not realized to a larger extent. For AICONT, we considered the average transaction speed of cryptocurrencies that are fastest, such as Algorand and EOS. The values for average transaction speed for the cryptocurrencies and related information are obtained using Statista²³ and Algorand Blog,²⁴ while the information regarding NFTs are obtained using Chainalysis.²⁵ The requirement suggests that the current iteration of communication system (5G) will not be able to meet most of the requirements, thus, the realization of Metaverse is closely tied with the emergence of sixth generation communication system which promises to have lesser delays, latency, and higher transmission bit rates, accordingly.

IV. ROLE OF B5G/6G IN METAVERSE

This section outlines the importance of B5G/6G services towards Metaverse in Sections IV-A and IV-B, followed by a comprehensive review of the state-of-the-art wireless communication technologies for immersive experiences in Sections IV-C and IV-D.

23. <https://www.statista.com/statistics/944355/cryptocurrency-transaction-speed/>

24. <https://www.algorand.com/resources/blog/role-of-transaction-finality-speed-in-nft-minting>

25. <https://blog.chainalysis.com/reports/chainalysis-web3-report-preview-nfts/>

A. IS B5G/6G NEED OF AN HOUR?

It is anticipated that Metaverse will be grounded on large-scale wireless cellular network technologies for the purpose of telecomputing, telecommuting, teleporting, teleoperating, telepresence, avatar interactions, and data mobility. The interactive and immersive experiences inside Metaverse will require very high data rates and low latency while transmitting high-resolution content. 5G networks could deliver data rates of up to <10GBs by exploiting the mmWave (30-300 GHz) spectrum [17]. This frequency and data rate remained successful in fulfilling the uplink and downlink throughput requirements of several multimedia applications ranging from live streaming to connected and autonomous vehicles. However, Metaverse is likely to interconnect a wide range of such services potentially involving holographic communication and real-time haptics, requiring milliseconds of motion-to-photon latency. Consequently, the bandwidth and throughput requirements for delivering such services will be 10^3 x more compared to the existing 5G-based cellular systems [20]. Therefore, 5G and pre-5G networks will not support the Metaverse for the following key reasons:

- 1) *Proliferation of devices*: Metaverse is expected to drive the growth of mobile and other IoT devices significantly. Thus, the connection density of 5G and pre-5G networks will not be able to accommodate the increasing number of devices.
- 2) *Multi-sensory communications*: Apparently, Metaverse will bring immersive services with multisensory communications that will pose stringent challenges to existing 5G QoS and QoE classes. Thus, 5G and pre-5G wireless systems will fail to provide a seamless experience to multiple immersive services such as avatar interactions or teleoperations in parallel.
- 3) *Complex and ultra-massive connectivity*: Metaverse is envisioned to build on prolific heterogeneous devices distributed in a highly dynamic, complex and ultra-massive network. In such a scenario, the existing 5G and pre-5G services catalog will not offer a reliable solution since those services are often designed for static and predefined optimization challenges.
- 4) *Decentralized services*: Decentralized intelligence will be a cornerstone in Metaverse driven heterogeneous multi-machine, multi-technology, multi-user, multi-application, and multi-device environments. Although 5G architecture can support the AI services on the network's decentralized edge, the edge intelligence

required by Metaverse is beyond the original goals of current 5G networks. The transmission rate offered by 5G can not guarantee the resilient edge AI because AI models will need to be subtle and highly dynamic while serving on the edge or other devices in Metaverse.

Pre-5G networks successfully supported the deployment of AR among retail applications, educational services, the gaming arena, and Google Maps [157]. VR/AR devices such as Google Glass,²⁶ Toshiba dynaEdge,²⁷ Microsoft hololens 2,²⁸ etc., and mobile applications such as IKEA Place,²⁹ Pokemon Go,³⁰ etc., have widely benefited from pre-5G networks. These apps and devices were not only self-sufficient but also leveraged Internet access via pre-5G access methods. Studies show that VR/AR users gained adequate experience via 4G LTE networks [158]. However, such networks are insufficient to meet Metaverse users' expectations. Metaverse will bring in next-generation multimedia such as real-time haptic feedback, high dynamic range (HDR), and stereoscopic video formats. The estimated data rate required to render a stereoscopic HDR 360° video of 8K resolution with 90 frames per second (FPS) is 200Mbps [157]. In addition, the holographic avatars will be rendered as a physical presence for remote users in Metaverse. The rendering of holographic avatars will be witnessed in situations where a doctor will be required to perform remote surgery, an engineer to troubleshoot in a remote factory, and a farmer to look after the grass and animals in remote geographic locations. Apart from typical graphical properties (e.g., resolution, depth, texture, or color), the holographs will be organized from various postures to ensure consistency in angles, frames, and slopes relative to the avatar. If an avatar is rendered in tiles of 4" x 4" dimensions, then an avatar with a 6' x 20" human size will require a transmission rate of 4.32 Tb/s [159]. According to a Third Generation Partnership Project (3GPP) analysis on the communication aspect of healthcare services, a remote AR-based surgery can operate on approximately <1ms of E2E latency and 12 Gbps of transmission rate considering an HDR 10bits stream of 4K resolution with 120fps [160]. Metaverse is envisioned to deal with longer durations of remote surgeries, operations, and other clinical trials. To offer immersive experiences in Metaverse, additional synchronization will be required apart from high data rates to ensure seamless transmission of multisensory content delivery and user experience. Such requirements are beyond the offerings of pre-B5G/6G systems, and non-3GPP access networks, including Wi-Fi, will be impractical due to the performance benchmarks and handover issues occurring from mobility [161]. Thereby, B5G/6G plays its role in

recognizing the demands mentioned above. In the subsequent section, we will entail the enabling technologies offered by B5G/6G.

B. WHAT B5G/6G BRINGS TO METAVERSE?

Since Metaverse is coined to be the next frontier in multimedia after VR/AR, it will encompass multisensory network services such as haptic and holographic communications. Soon users will undermine the QoE delivered by VR/AR and demand new lifelike multimedia experiences, unlike today's not-real-enough VR/AR experiences. Metaverse applications involving avatar interactions aided with novel communication modalities such as avatar-to-avatar (A2A), avatar-to-human (A2H), and human-to-avatar (H2A) will drive the majority of the Internet traffic by 2030 [162]. Thereby, the services provided by B5G/6G have a crucial role in realizing the lifelike experiences in Metaverse.

1) 5G SERVICES TOWARDS METAVERSE

5G networks offer three prime categories of services listed by the International Telecommunication Union (ITU)³¹: uRLLC, mMTC, and eMBB to handle the requirements of extremely low latency, enormous content transmission and high computations. eMBB traffic requires a gigabit/s level of the transmission rate. At the same time, uRLLC expects high reliability of 99.999% with ultra-low-latency of 0.25 ~ 0.30 ms/packet, and mMTC requires highly dense connectivity with significant energy efficiency. However, uRLLC can only provide a data rate of up to 10 Mbps which might fit in a few applications of VR/AR. In contrast, eMBB can be suitable for delivering ultra-high throughput in order to meet the requirements of Metaverse users accessing multisensory content ranging from teleoperations to holoconferences to telesurgeries with 3D 4K resolutions.³² In addition, it can offer the minimum guaranteed delivery of 100 Mbps to users. Therefore, eMBB can play a crucial role in Metaverse's gaming and entertainment paradigm by providing mobile users with 100-200 Mbps downlink with a peak threshold of 250 Mbps and latency of <100ms [163].

An evolution of VR technologies can be seen in Figure 10. From basic VR video streaming to interconnected VR to a fully wireless interconnected VR, a series of stages can be seen [20]. However, unlike conventional video streaming, wireless streaming in Metaverse may require transmitting enormous omnidirectional visual content with a latency of <20ms. The success of such an immersive virtual experience is highly reliable on a smooth transmission mechanism of ultra-high-resolution visual content along with a highly subtle tactile feedback in downlink networks. As discussed in Section IV-A, it is obvious to rely on the B5G wireless technologies to support the immersive virtual applications. Therefore, mmWave has progressed towards standardization

26. <https://www.google.com/glass/start/>

27. <https://us.dynabook.com/smartglasses/products/index.html>

28. <https://www.microsoft.com/en-us/hololens/>

29. <https://www.ikea.com/au/en/customer-service/mobile-apps/say-hej-to-ikea-place-pub1f8af050>

30. <https://pokemongolive.com/en/>

31. <https://www.itu.int>

32. <https://www.5g-eve.eu/>

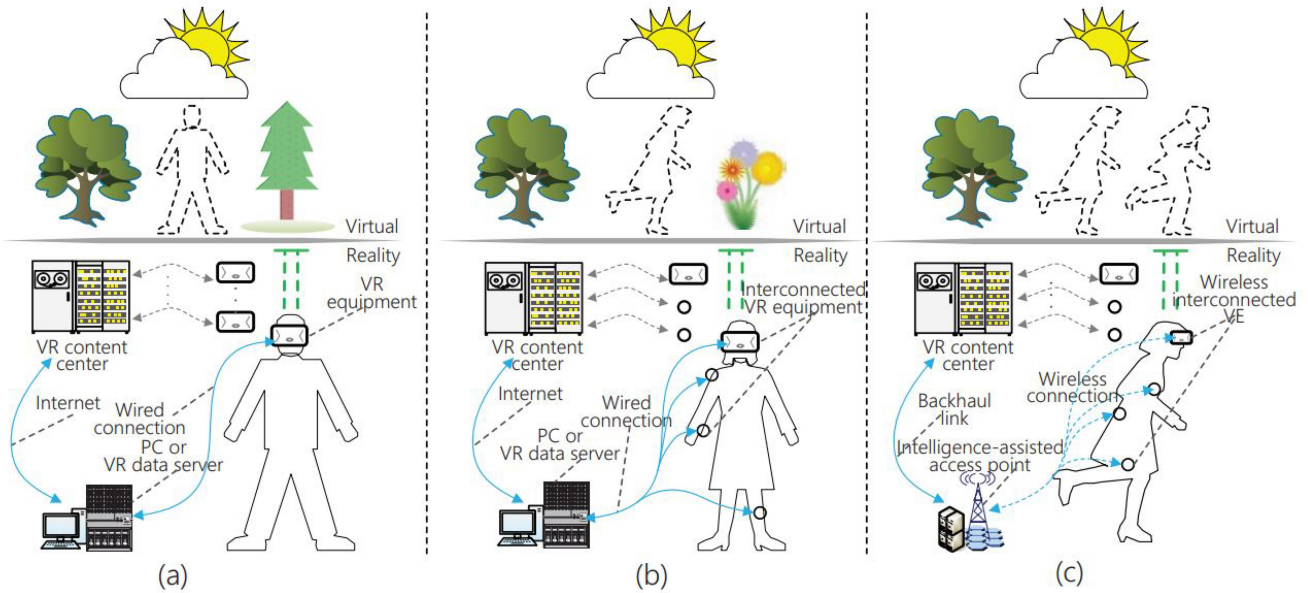


FIGURE 10. Evaluation of VR experiences: a) VR over wired connectivity, b) VR over interconnected network, and c) VR over fully wireless connectivity [20].

by 3GPP in B5G wireless systems [19]. Simultaneously, researchers have also explored the potential of mmWave mobile networks in realizing the wireless bandwidth requirements of VR applications. According to [20], mmWave is able to successfully deliver high data rates with low-latency transmission for several VR applications. Similarly, the mMTC service can support dense mobile connectivity of up to 1 million devices per square kilometer which is approximately 10x greater than 4G LTE networks. A study by the European 5G Observatory³³ reported the data obtained from 180 trials to assess the capacity of 5G in a dense urban area of Finland. The mMTC service was able to deliver a realistic data rate of 700 Mbps to 1 Gbps by accommodating a reasonable user density. Based on the overall analysis, 5G service equipped users' devices with average data rates of 1-4.5 Gbps with a delay of <5ms [164].

Since a few Metaverse applications will require a data rate ranging from 100 Mbps to a few Gbps with 99% reliability and a delay of <5ms, 5G networks may fulfill these requirements efficiently. Apart from that, Metaverse users will utilize the diverse features of mobile systems ranging from display and sensing capabilities to near-user computing resources [61]. In addition, the recent innovations in vision and tracking technologies such as depth, 360° resolution and precision have supported the idea of user's interactions with the surroundings. These capabilities are not limited to smartphones; many devices such as fitness watches, smart TVs, game consoles, and autonomous vehicles also possess these features. These devices can leverage the services of 5G with single-digit latency, high throughputs (i.e., 10x > 4G), five-nines of network reliability and dense network coverage (i.e., > 10-100x) [165]. In 2021, 5G smartphones entered the

commercialization phase and were expected to spread in the global market within the next few years [166]. The growth of these devices with seamless connectivity will certainly form the basis of several immersive services such as tele-classrooms, tele-surgeries, and teleoperations. Nevertheless, to deliver such services with a sufficient QoE requires very high data rates within a range of 1 Gb/s to 1 Tb/s which can be supported by B5G cellular and underlying transmission networks [167].

2) 6G SERVICES TOWARDS METAVERSE

6G networks are envisaged to provide ubiquitous intelligence with abundant compute power and high-speed wireless data fidelity over the air, space, and sea as shown in Figure 12. 6G services have been defined in terms of the real-time mesh of physical and cyber worlds, with a fine-grained focus on the interactions among physical, digital, and biological (human-centered) worlds [168], [169]. An immersive merger of cyber and physical space is likely to bring new platforms in the shape of embodied Internet, providing 6G based Metaverse applications and other cyber-physical systems (CPS). 6G will exquisitely enhance user experience in the Metaverse since its services are primarily human-centric instead of data-centric. Consequently, Metaverse users and the associated processes, user equipment, and the network will be holistically integrated to provide a plethora of immersive applications.

Moreover, 6G networks will empower edge intelligence through on-device machine/deep learning and distributed AI that will transform the "connectedness with intelligence" for not only human-centric but also machine-centric applications [170]. In Metaverse, 6G will enable neural and haptic sensory communications with an integrated holographic reinforcement [38]. 6G will also fulfill the

33. <http://5gobservatory.eu/5g-trial/major-european-5g-trials-and-pilots/>

requirement of Internet-of-Everything by featuring the network-in-box management and virtualized services that will motivate the massive multiple access points to shape a distributed (cell-less) multiple-input and multiple-output (MIMO) system [171]. In contrast to 5G systems, 6G supports terahertz frequency bands and is liable to provide 1 Tbps of data rate with an E2E delay of 0.1ms [172]. It also supports extremely reliable low latency communications (eRLLC)-based services along with a reliability rate of 99.9999999%. In principle, Metaverse users can achieve high QoE by leveraging the following 6G services: support for multi-dimensional holograms, ultra-massive data-transmission rates to support HDR 360° multimedia with 4K/8K resolution, extreme low-latency and high precision for haptics required in 3D-printing, telepresence, immersive multi-user gaming, and responsive digital twins in industry 5.0. Furthermore, these 6G services will be underpinned by AI, such as federated learning, split computing, and distributed deep reinforcement learning to reduce network congestion and improve the user QoE [25].

In summary, 6G will surpass the previous generations by catalyzing the wireless revolution from “connectivity” to “connectivity with intelligence” with the following key emerging services and utilities:

- *High data rates:* The usage scenarios under ultra mobile broadband (uMBB) will exploit significantly higher data rates as compared to the ones in 5G eMBB services.
- *Dense connectivity:* The ultra-massive machine-type communication (uMTC) scenario will empower use cases where a relatively higher and massive number of connections in a certain space will be required simultaneously as compared to the ones provided in 5G-mMTC services.
- *High reliability and precision:* The services under ultra-high precision communication (uHPC) require a very high degree of precision, reliability and accurate positioning, making them suitable for mission-critical applications as opposed to 5G-URLLC services. These services ensure stringent service level guarantees can be enforced independently or in part with each other.
- *Air-to-ground connectivity:* The services under extended 3-dimensional coverage (e3DC) will be able to exploit the in-space non-terrestrial satellite communications by utilizing the ground-based terrestrial mobile networks. The realm of in-space networks includes drones, high-altitude platform stations, and air-borne to provide multi-dimensional coverage across the globe.
- *Communication meets computation:* The proliferation of emerging smart devices will urge the need for an autonomous and distributed computing framework to facilitate key technologies such as split computing and federated learning [170]. 6G will facilitate the computation-centric communication that will ensure the required QoS provisioning by trading off the communication resources in order to achieve sufficient computational accuracy.

- *Context-driven communications:* The 6G network context, such as network architecture and bandwidth, will navigate the provisioning of 6G uMBB services to the users. It will significantly benefit the Metaverse applications since the physical context, such as the user’s location, mobility and social connections, will be highly dynamic, eventually leveraging the agile and adaptive service provisioning of 6G networks.
- *Event-driven communications:* 6G networks will ensure the orderly provisioning of uHPC services based on certain characteristics of emergency or disaster events. The highly dynamic spatio-temporal attributes of users and devices, network traffic and infrastructure will play a key role in resource allocation in 6G-uHPC application scenarios.

Apart from the above services and their usage scenarios, 6G can also offer a hybrid of these services to meet the extreme demand for new performance metrics in the Metaverse that are unlikely to be achieved by 5G and pre-5G networks. For instance, an application can leverage the combination of uMBB and uHPC, subject to the fulfillment of requirements of both services simultaneously. Similarly, uMTC and uHPC can be combined for a certain application if the needs of both services can be met simultaneously [103].

C. IMMERSIVE EXPERIENCES OVER WIRELESS

Immersive experiences are facilitated through virtual worlds, where the users experience a fully immersive environment, thus creating a meta-world that projects the real-world scenarios. State-of-the-art VR applications are embedded with a dynamic streaming framework that automatically adapts the bitrate of the XR content according to the network bandwidth and user’s geolocation [173]. Although the 5G legacy has remained capable of providing rudimentary XR support, scaling the adoption of XR devices and applications over wireless networks requires new research and engineering directions. Recently, 5G and beyond has paced further in boosting the XR performance by introducing various heterogeneous improvements in not only XR-specific entities but also service-related advancements. In contrast, a recent study by Meng et al. [174] developed a prototype to enhance the immersive experience in metaverse by minimizing communication load while ensuring accurate synchronization between the physical world and its digital models. Table 8 shows several studies that investigated the role of state-of-the-art B5G/6G technologies for immersive experiences.

mmWave for Wireless VR: Towards this end, the 3GPP is involved in standardization activities for mmWave communications in B5G/6G systems [170]. In the meantime, academia is also exploring the potential of mmWave mobile networks to support wireless VR streaming over high bandwidth [22]. The use of mmWave communications enables high transmission rates and low delay transmissions so that wireless VR applications can be seamlessly supported. In addition, the abundance of wireless bandwidth can

further alleviate the scarcity of transmission rates through mmWave communications. Researchers generally consider 60 GHz mmWave wireless technologies since it is the only standardized mmWave wireless technology that has been identified so far based on the IEEE 802.11ad [175]. For example, authors in [176] explore the potential of a 60GHz wireless channel to simultaneously process the large-scale multimedia content delivery in distributed VR platforms.

MEC for Wireless VR: Another challenge in supporting VR experiences is that the videos must also remap pixels from a viewing sphere to a 2D viewport in order to distinguish their content form from traditional videos. The rendering process involves complex matrix mult-add operations and is extremely computationally intensive. Hence, the power consumption of virtual reality videos is significantly higher than other forms of video [177]. As a result, this will bring great challenges to the ubiquitous applications of wireless VR, as the continuous rendering of viewports will lead to exhaustion of battery and will eventually shorten the battery life. To address this challenge, various scenarios of MEC and caching have emerged as promising solutions to support wireless VR [167]. The deployment of MEC and caching paradigms at the mobile network edge can enable some computation tasks to be handled by in-network computing capacity. Additionally, some popular VR content and computational outputs can be cached to reduce the amount of repetitive computation and transmission. For example, in the article [178], the theoretical architecture of a hybrid mobile computing system is presented concurrently that combines the processing abilities of cloud servers, MEC servers and end devices along with the caching capabilities of MEC servers. Similarly, according to [171], VR tasks can be divided into several sub-components, and part of the sub-component can be cached using the mobile device's caching mechanism.

mmWave meets MEC for Transmission Efficiency in Wireless VR: Furthermore, several studies have indicated that introducing FOV into 360° video will reduce up to 80% of the bandwidth requirements compared to delivering 360° video, hence lowering the overall necessary transmission data rate [180], [181]. For example, authors in [182] analyze the tradeoff between homogeneous and heterogeneous FOVs for a MEC-based mobile VR delivery model regarding computations and caching tasks. In addition, several methods have been proposed that take advantage of the FOV of users, for instance, introducing FOV prediction [183] and segregating different types of VR frames and multicasting them [184]. Based on the above discussion, it is apparent that more schemes can be developed if mmWave communication is combined with MEC-based FOV mechanisms. For instance, Liu et al. use mmWave and sub-6GHz link to transmit a panoramic virtual reality video (PVRV) stream by encoding the viewport and rendering the standby tiles according to different quality levels [179], as shown in Figure 11. Similarly, Gputa et al. present A multiple-layer streaming

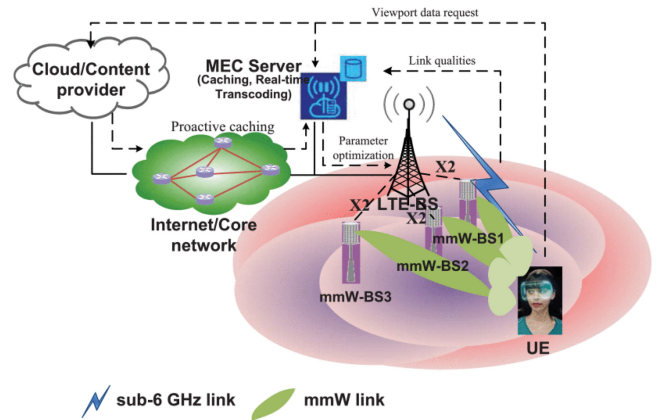


FIGURE 11. Transmission of a panoramic virtual reality video (PVRV) stream using mmWave and sub-6GHz link on a MEC framework [179].

scheme in which the base layer is encoded and transmitted via Wi-Fi [185]. In contrast, a number of enhancement layers are transmitted via the mmWave access point. Therefore, a fusion of mmWave and MEC-based FOV schemes can reduce bandwidth requirements while reducing the transmission delay when compared with 360° videos.

Immersive fidelity with THz communication: Metaverse will use 360° videos and MAR applications to bring immersiveness, as well as AI-driven applications with ubiquitous integration. Due to this, vast amounts of data will be exchanged; hence the demand for radio frequency bandwidth spectrum will surge rapidly. The existing mmWave technology cannot satisfy this demand. Consequently, switching to the terahertz and sub-terahertz bands would be imperative. THz communications are able to deliver ultra-high throughput and low latency by supporting data-intensive applications such as VR/XR over wireless personal area networks [27]. Several studies have leveraged the unique benefits of THz to be implemented with 6G for immersive experiences. In a study by Du et al., authors examined the problem of providing a high-quality immersive VR video service [186]. In particular, the authors exploit the THz channel with MEC integration to optimize the immersive VR rendering, power management, and offloading viewports while satisfying the QoE constraints. Similarly, Chen et al. [187] investigated an immersive application involving VR users transmitting 360° images to a backend server. They formulated a problem to maximize the users' successful transmission probability by optimizing the downlink image transmission and the rotation of the surrounding images. Their proposed optimization problem involves a transfer learning approach consisting of liquid state machines to enhance the convergence speed by transferring the learned transmission into a new one. Despite the promising QoS delivery by the THz communication system, it still has significant propagation losses and water-molecule absorption losses due to high transmission frequency [188]. For this reason, THz has remained effective for indoor service delivery. For

TABLE 8. Summarising the role of state-of-the-art B5G/6G technologies in the context of Metaverse.

Authors & Year	Reference	B5G/6G Services	Application scenario
Mourtzis <i>et al.</i> , 2017	[195]	HMDs, mobile edge, and cloud computing	AR-based tele-maintenance using a cloud-based and serviced oriented system
Cheng <i>et al.</i> , 2018	[196]	eMBB, mMTC, URLLC, and IIoT	AR/VR and digital twin based industrial manufacturing
Erol <i>et al.</i> , 2018	[197]	edge caching, edge mining, computational offloading	AR/VR access pattern in virtual tourism
Ren <i>et al.</i> , 2020	[198]	D2D communication, cloud computing, on-device computing, and computational offloading	Edge-assisted multi-user cooperative environment for mobile web AR applications
Pengnoo <i>et al.</i> , 2020	[24]	digital twins, THz links, and metasurface reflectors	Improving transmission links for potential data-intensive applications in Metaverse
Zhou <i>et al.</i> , 2021	[199]	MEC, 5G antennas, computational handoff, RNI, and gNB/ng-eNB	Improving QoE for MAR based gaming such as collaborative assembly of a virtual object
Liu <i>et al.</i> , 2021	[189]	MEC, THz network, RIS, and federated learning	Empowering immersive VR experiences using prediction, rendering, and transmission of 360° content
Fantacci <i>et al.</i> , 2021	[27]	HRLLC, THz channels, SNC, and edge computing	Improving QoS for edge-assisted VR experiences by minimizing the E2E transmission delay
Ng <i>et al.</i> , 2021	[200]	edge intelligence, unified resource allocation, and VSPs	Improving QoS in educational applications of Metaverse by optimising resource allocation on users' demands
Ren <i>et al.</i> , 2022	[201]	edge node localisation, service migration, load balancing, distributed edge AI	Orchestration of distributed edge services for location-based mobile AR systems
Zhang <i>et al.</i> , 2022	[202]	edge caching, computational offloading, decentralised computing	Scaling object recognition services for seamless mobile AR experiences
Ghoshal <i>et al.</i> , 2022	[18]	mmWave, cloud computing, uplink data offloading	Realising cloud-based multi-user AR experiences with 5G mmWave
Van <i>et al.</i> , 2022	[203]	MEC, URLLC, digital twins, and edge caching	Improving QoE of digital twins in Metaverse by jointly optimising the computing, communication, and storage resources
Bhattacharya <i>et al.</i> , 2022	[5]	TI, URLLC, H2M control, blockchain, xAI, and decentralised computing	Improving quality and precision of tele-surgeries for patients, virtual hospitals, and doctors in Metaverse
Kang <i>et al.</i> , 2022	[204]	MEC, federated learning, IIoT, blockchain, and AoI	Empowering immersive Metaverse experiences through user-defined privacy-preserving incentive schemes
Meng <i>et al.</i> , 2023	[174]	sampling, communication, prediction, and hardware prototyping	Empowering immersive Metaverse experiences through synchronization between the physical world and its digital models

instance, Liu et al. propose a deep reinforcement learning (DRL)-based strategy to efficiently maintain the long-term QoE in THz-based immersive systems [189]. Specifically, authors have studied a joint use of THz and RIS to create a VR network in an indoor scenario with an aim to enhance downlink transmission. To achieve the aim, the authors utilize the current and historical viewpoints of VR users obtained from real VR datasets to train a gated recurrent unit (GRU) model for predicting the dynamic viewpoint preference of VR users. Table 8 shows several studies that investigated the THz channels for immersive experiences.

D. HOLOGRAPHIC TELEPRESENCE IN METAVERSE

Metaverse users would be able to see high-quality, three-dimensional digital representations of people using Holograms and without wearing HMD. Future networks (i.e., B5G/6G) will be able to support extremely low latencies and ultra-high data rates with high reliability in order to underpin the holographic communication that will facilitate Metaverse users to fully immerse in gadget-free communication [22]. For example, a 6G network with 0.1ms of latency supported by an ultra-high bandwidth of Tbps can be leveraged for HT [190]. In order to evaluate HT applications, there should be seamless and quality connections between users, which requires an extremely low-latency data transmission rate and massive low latency. A number of factors affect the required data rates, such as the method used to construct a hologram, the type of display and the number of images that need to be synchronized. For example, a typical hologram based on the point cloud techniques requires 0.5–2 Gb/s, whereas a large-sized hologram may require up to a few Tb/s [191].

The transmission of such holograms may be underpinned by using data compression techniques, but even then, holograms are likely to require vast amounts of bandwidth. Therefore, latency and reliability become two critical key performance indicators (KPIs) for HT. Within Metaverse, HT will be able to launch a number of human-type communications, including telesurgery, immersive education, teleoperations, and the Internet of Skills (IoS) [192]. Due to HT's high sensitivity to latency, these applications have strict requirements for round-trip delay. Thus, it is important that the communication link for these applications be ultra-reliable to avoid packet losses which may lead to disastrous events. To overcome that, mobile B5G/6G networks have been considering URLLC as one of the new application scenarios to support the above applications [193]. It is expected that with 5G New Radio, the radio access networks (RANs) can achieve a 1 ms delay with 10⁻⁵–10⁻⁷ packet loss probability. This includes 0.5 ms uplink transmission and 0.5 ms downlink transmission [194]. In addition to that, 6G can provide URLLC with 1 Tbps of data rate and E2E delay of 0.1ms using THz frequency bands to support HT in Metaverse.

V. NEXUS OF AI AND 6G FOR METAVERSE

This section outlines the interplay of B5G/6G and AI towards Metaverse. In Section V-A, we discuss the role of 6G in realising the pervasive and ubiquitous AI services that are discussed in Section III for Metaverse environments. Section V-B explains the role of AI in making autonomous 6G network infrastructures for Metaverse, followed by the joint role of AI and 6G for tactile and immersive experiences in Section V-C.

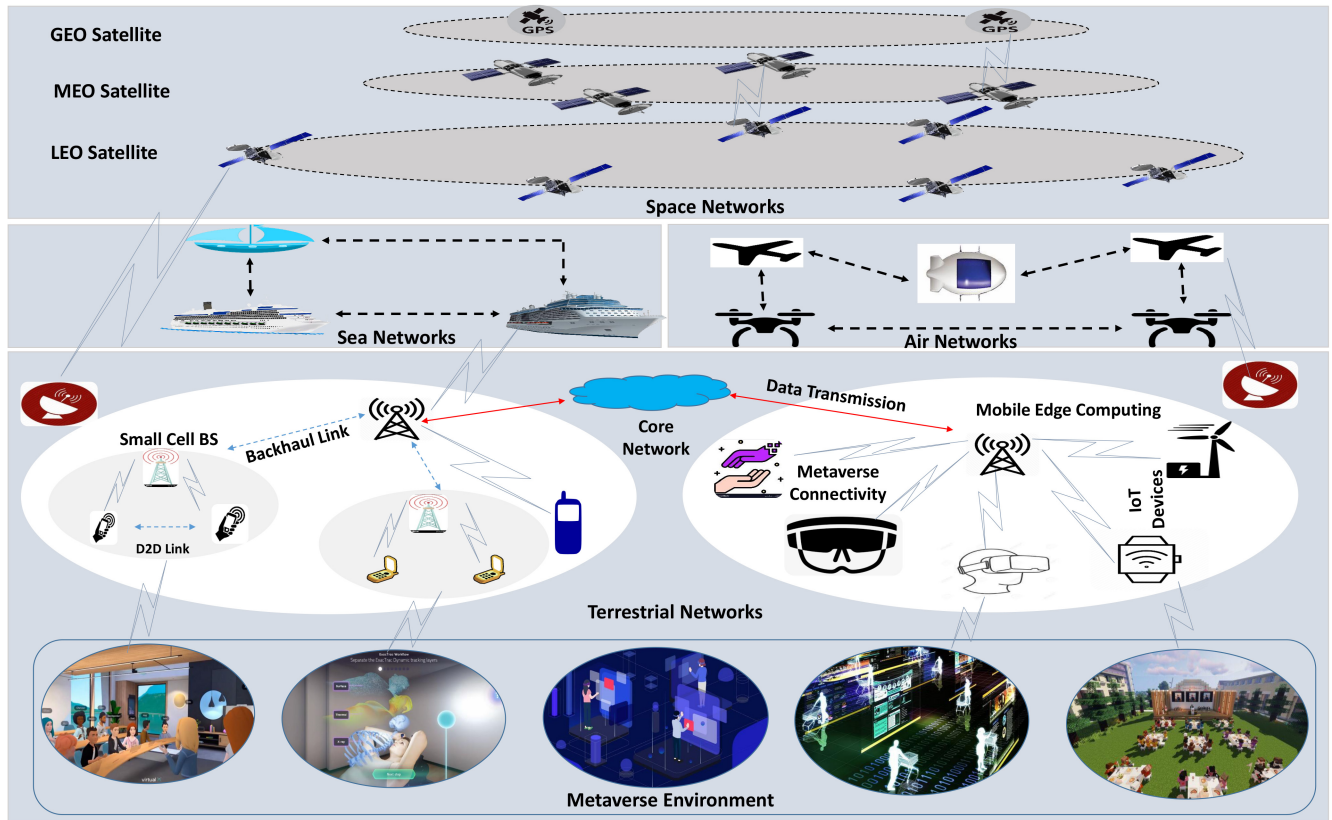


FIGURE 12. An illustration of a large-scale SAGSIN in Realizing Metaverse.

A. 6G-DRIVEN PERVERSIVE AI FOR METAVERSE

Metaverse is envisioned to be extending people's life by allowing them to live, work, and play seamlessly for unlimited durations. This can only be realized if the Metaverse has a strong relationship with "ubiquitous connectivity with intelligence," i.e., B5G/6G, AI, and space-air-ground-sea integrated network (SAGSIN) as shown in Figure 12. In essence, 6G will support pervasive intelligence by reducing the potential latency of virtual experiences and will allow developers to develop better virtual experiences in the Metaverse where millions of concurrent users can share an immersive 3D space with each other. In such cases, the location of sender and receiver might be remote; thus, the challenge is to support dense connections (e.g., 10^7 users/km²), where multiple users can transmit and receive 360° video content or real-time human-like holographs in parallel [28], [30]. Such a sheer amount of data fidelity will require ultra-high bandwidth with heterogeneous hardware for hosting AI services discussed in Section III, requiring extremely low-latency communications for transferring model parameters or performing AI inferences.

Since 5G's rollout, the first set of promising technologies along with architectural evaluation were polar codes, massive MIMO, mmWave, and MEC. These unique 5G services were able to support AR/VR applications by providing ubiquitous connectivity. AR/VR users leveraged 5G-eMBB

service to achieve <100ms latency with a throughput of 100-200Mbps [29]. Several experiments were carried out further to evaluate 5G's performance in realistic mobile environments. For example, the 5G-PPP (The 5G Infrastructure Public Private Partnership, 2018)³⁴ consortium reported a data rate of approximately 3Gbps having 2ms of latency on their Bari-Matera installation in Italy.³⁵ This experiment was carried out with the combination of 5G services with LTE technology.³⁶ Another experiment provides data from around 180 trials and investigations conducted by the European 5G Observatory. In this scenario, the trials were conducted for a number of weeks in urban areas of Finland, therefore possibly with a reasonable density of users, and results suggest that the most realistic data rate was approximately ranged from 700 Mbps to 1 Gbps. According to the final experiment results, users' devices realized 1 to 4.5 Gbps in average data rates, with less than 5 ms latency. It has widely been acknowledged that AR/VR applications require latency lower than 5ms, with average throughput between 100 Mbps to a few Gbps, and reliability of at least 99%, meaning that 5G performance is sufficient to support these needs [11].

34. <https://5g-ppp.eu/5g-trials-2/>

35. <https://www.fastweb.it/fastweb-plus/digital-magazine/5g-matera-fastweb/>

36. <http://www.barimatera5g.it/>

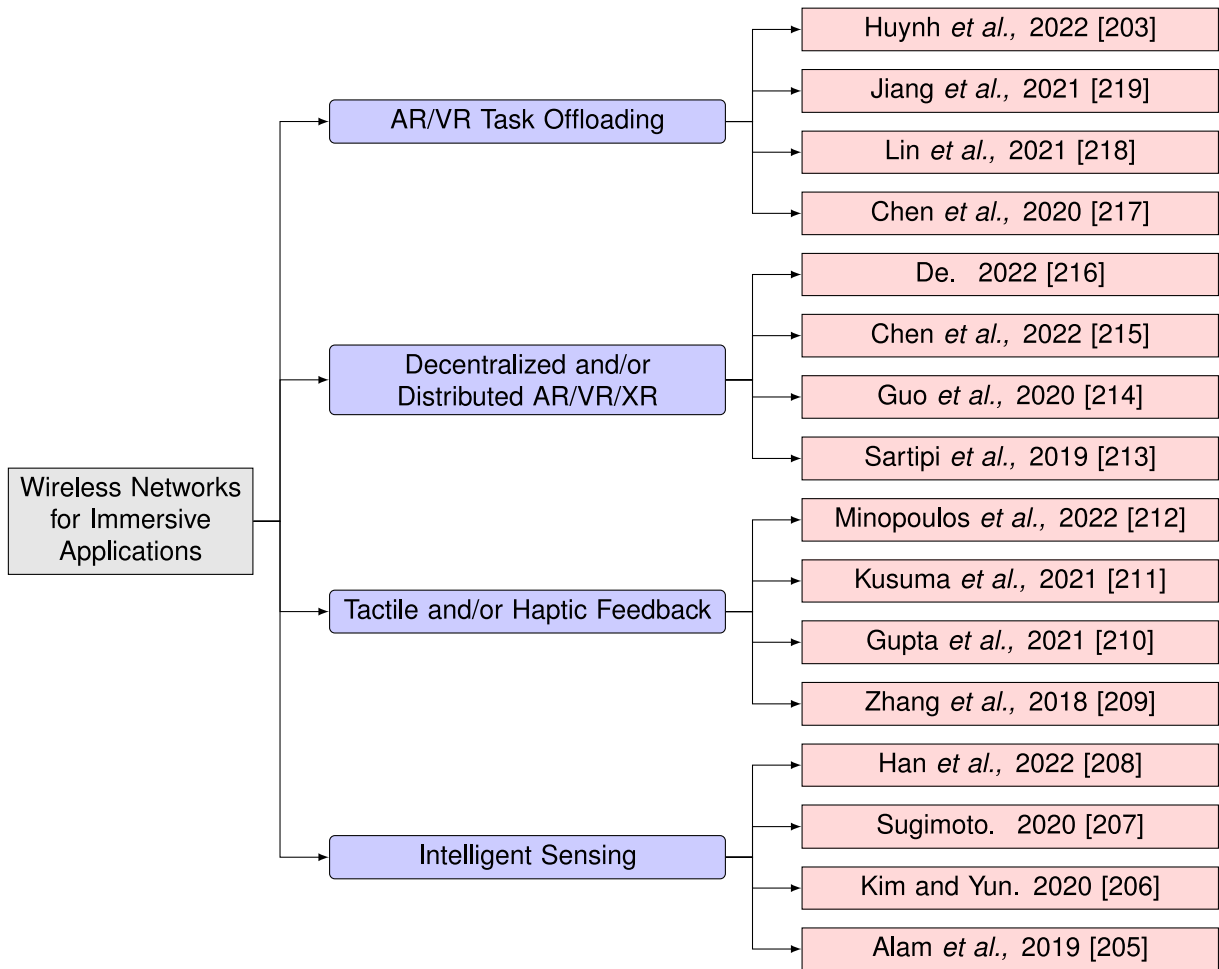


FIGURE 13. Taxonomy for the classification of literature on 5G/6G Wireless-empowered Immersive AR/VR Applications.

Metaverse is supposed to be accessible from anywhere at any time; thus, it is presumed that 5G networks will fail to provide coverage in some parts of the globe, such as remote areas, oceans, mountains, deep forests, and airspace. This shortcoming of 5G can be overcome by 6G, which is expected to provide ubiquitous global coverage as shown in Figure 12. As part of 6G systems, data collection, transportation, and utilization will take place in real-time and anywhere at any given time, hence, catalyzing immersive applications and services for Metaverse. 6G will particularly emphasize ubiquitous AI, bringing artificial general intelligence into every aspect of Metaverse through a hyper-flexible architecture. On top of that, a 6G network will be well suited for several Metaverse applications involving deep learning because it can generate a great deal of data and perform computation and storage at the network edge [34]. In summary, 6G networks can not only host personalized AI services but also cater to the needs of dense user connectivity with low-latency-high-reliability communications. For instance, a case study by Adeogun et al. entails a framework involving a short-range wireless isochronous real time (WIRT) environment for a 6G communication

system. Authors developed a WIRT in-X sub-network with roundtrip communication latency lesser than 0.1ms with an outage probability $< 10^{-6}$ [220]. A multi-GHz spectrum for enhancing spatial service availability is considered part of a dense IoT scenario with up to two devices per m^2 . Based on their results, it can be observed that cycle times are 10x shorter than the latency target achieved via 5G radio technology, i.e., $< 0.1\text{ms}$ [220]. Therefore, Metaverse services involving novel communication modalities such as A2A, A2H, and H2A can leverage great benefits from 6G. We present a clear taxonomy of state-of-the-art for 5G/6G wireless-empowered immersive experiences in Figure 13.

B. AI-LED AUTONOMOUS 6G NETWORKS FOR METAVERSE

The success of the Metaverse experience will highly rely on the seamless and sustainable integration of physical space into virtual 3D space. Modern technologies (i.e., XR, AI, and 6G) can contribute to the interconnected Metaverse by ensuring interoperable coherence between the Metaverse and the physical world (e.g., physical objects in the real world are compatible with virtual objects in the Metaverse) [1].

In this regard, a minor disconnect between Metaverse and the physical world can cause only a mere disturbance to the users; however, as the prevalence and utility of Metaverse increases, such a disconnect in immersion may leave a long-lasting impact on the life-critical applications of Metaverse. Therefore, a communication system for Metaverse must be capable of providing a stress-free and extremely reliable experience for sheer users.

1) SELF-X NETWORKS

Based on the above-discussed Metaverse requirements in Section IV-A, it is critical for 6G networks to have an intelligent and autonomous adjustment capability in order to meet various performance requirements, such as full coverage sensing, ultra-low latency, and ultra-high reliability, and persistent security [221]. At present, there is difficulty in dynamically adapting to the continual changes in user needs and network environments that alter the operating paradigms of today's networks, which mainly rely on rule-based algorithms as their core. A further constraint is the inability to effectively accumulate the QoE of network operations, which in turn prevents continuous improvement in the capabilities of the network [222]. In other words, it is not currently possible for networks to self-evolve under the existing operating procedures. Thereby, whenever there is a need to upgrade or improve something, much human expertise and effort are needed. As 6G networks grow in geography and complexity, manual intervention is unacceptable and unreliable for the networks to operate at such a scale. Therefore, to overcome this hurdle, European telecommunications standards institute (ETSI) recently initiated 2 groups, i.e., zero-touch service management (ZSM)³⁷ and experiential networked intelligence (ENI)³⁸ having focused on the use of ML and DL to manage and orchestrate the resources of a network in a fully automated way. The key objective of ZSM and ENI is to add the component of "intelligence" into every block of future networks in order to realize intelligent and self-evolution abilities within the 6G-and-beyond networks [223].

2) AI FOR NETWORKS

The inception of Metaverse will exceptionally pose new challenges for 6G networks that will require support from AI, particularly deep reinforcement learning, and deep federated learning as shown in Figure 14. In the traditional sense, the Metaverse is not like a digital twin, which is a virtual representation serving as the equivalent to a physical object [161]. In essence, Metaverse will offer possibilities for scenario creation that differ from reality and allow them to be run at their own time and with their own rules, requiring dynamic support from 6G and AI nexus. As such, several researchers have already explored the use of AI for supporting 6G networks in challenging environments. For example, the

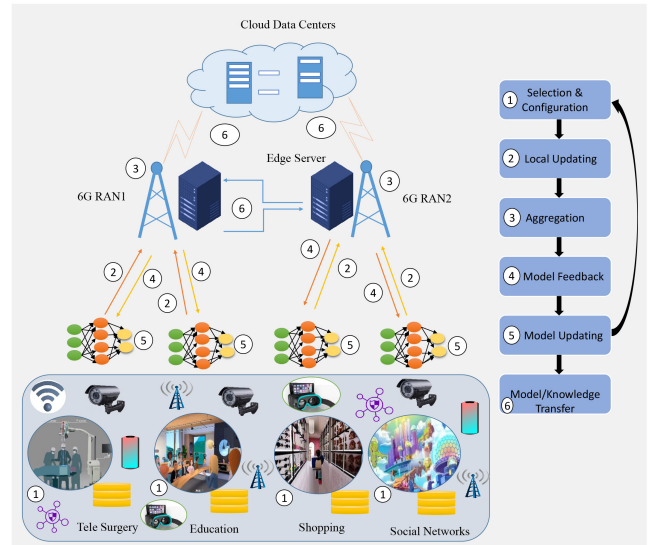


FIGURE 14. FL architecture and distributed training procedure in Metaverse.

dutch double auction mechanism and DRL were combined in [224] to improve transaction efficiency in the Metaverse. The ability to make intelligent decisions based on RL is a key enabler for the development of 6G networks for Metaverse, especially those with strict QoS requirements. Metaverse services can benefit from RL optimization techniques if they are well designed because they enable the ability of self-healing, self-optimizing, and self-organizing for the 6G networks. For instance, Tariq et al. propose a DRL-driven approach for proactive resource management and intelligent service provisioning in 6G networks for a digital-twin application [14]. However, this approach can suffer from a significant deficiency in the performance of AI models. Particularly, for a highly distributed Metaverse application where users are only supposed to interact continuously for the purpose of AI model training without accessing the other user's data due to strict security restrictions as shown in Figure 14. To retain the performance of such AI models, recently Kang et al. proposed an architecture for a decentralized Metaverse application based on federated learning integrated with blockchain [204]. Based on their architecture, the local AI model can be optimized by horizontal cooperation of multiple end nodes (edge devices), which eventually retain the performance of AI models over time. Hence, the use of AI to optimize the network architecture and improve the performance of 6G networks is therefore proving to be a promising means of enhancing the Metaverse experience. In Figure 15, we present a clear taxonomy of state-of-the-art for AI-driven immersive experiences over wireless.

C. AI AND 6G FOR TACTILE INTERNET IN METAVERSE

In the Metaverse, the tactile Internet will dominate haptic communication for mission-critical virtual services with

37. <https://www.etsi.org/committee/zsm>

38. <https://www.etsi.org/committee/ENI>

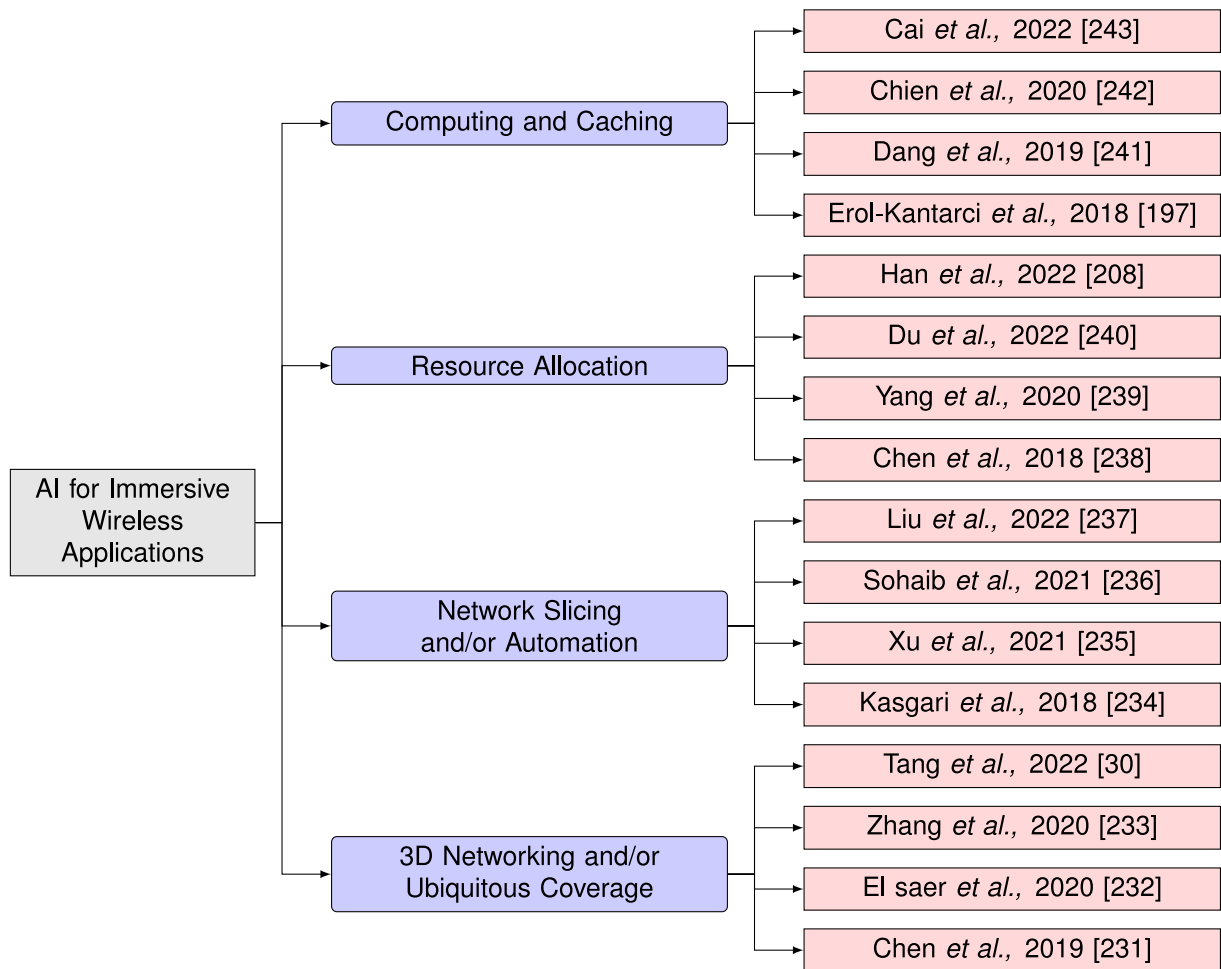


FIGURE 15. Taxonomy for the classification of literature on AI-empowered Immersive Wireless Experiences.

touch and actuation in real-time while facilitating timeliness of information delivery for intelligent and interconnected meta-worlds. TI is expected to underpin human-to-human and human-to-machine interactions in a way that the time duration between actions and feedback should be much lower than the physical world reaction times [12]. For this reason, it is necessary that the TI has a 1ms delay due to the nature of the haptic signals and how humans perceive them. There is, however, a limit to the latency that can be supported by pre-5G networks, which is approximately 25ms [13]. Therefore, B5G/6G networks are anticipated to outperform previous generations in terms of performance by providing a sustainable infrastructure that will ultimately realize the TI for immersive services. 5G can aid in TI realization for Metaverse by addressing the key communication and computation challenges leveraging the following 3 important enabling technologies: edge computing, network functions virtualization (NFV), and software-defined networking (SDN) [225]. These enabling technologies can be combined in order to provide sophisticated solutions for the network architecture. For instance, researchers in [226], [227] explore how SDN can be leveraged efficiently for the edge computing

based 5G networks. In another study by Aijaz et al. [15], authors investigate how edge computing, SDN, and NFV can be utilized to create a novel, sustainable and general-purpose 5G architecture to realize TI applications. In essence, their approach is motivated by the virtualization concept of NFVs, which can dynamically instantiate an end-to-end 5G network according to the user's applications' requirements. Therefore, it can be observed that bringing computing capabilities closer to the user equipment and using SDN to control it centrally (i.e., limiting intermediate nodes) can foster latency reduction through edge computing and SDN [227], [228].

It is also important to stress that the TI should not be limited to the context of 5G, as discussed above in relation to the Tactile Internet and 5G, but that it should take a broader position than that. Many research efforts are underway that aim to achieve the TI over other technologies (e.g., wireless communication with sub-GHz technology, wireless local area network (WLAN) and wireless body area network (WBAN), and combinations of technologies similar to these). Despite 5G's potential to enable URLLC applications in general, as mentioned in Section IV-A, its design objectives were not customized to the TI's specific

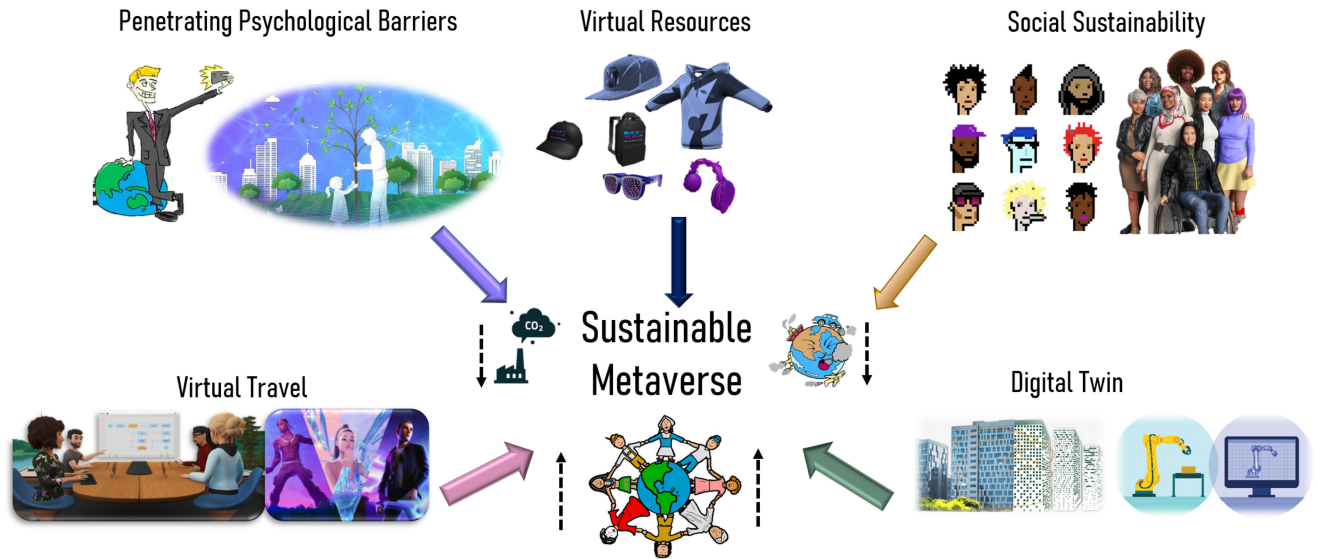


FIGURE 16. Summarization of Sustainable Metaverse.

features and requirements. In response to the shortcomings of 5G, both industry and academia have gathered a great deal of interest in next-generation 6G systems, which are expected to support a variety of immersive applications from multi-sensory communication to XR [229]. Apart from that, TI lays out a sheer amount of opportunities to leverage AI, particularly deep learning to segregate the perception of humans from the overwhelming transmission delays which are usually experienced in wide area networks (WANs) [230]. AI can certainly play a key role in fulfilling the 1ms latency requirements using these networks. Although communication-based enabling technologies can overcome the end-to-end latency challenge, their efficiency can not go beyond the scope of 150km due to their dependency on the speed of light. Therefore, deep learning-based predictions can be widely utilized to achieve 1ms latency by ruling out the 150km constraint on these networking technologies [194].

VI. METAVERSE USECASES CONCERNING SUSTAINABILITY AND PRIVACY

This section outlines the sustainability issues in the Metaverse with respect to virtual resources, virtual travel, digital twins, psychological barriers, and social sustainability, respectively. The issue of sustainability is at the helm of affairs when discussed business strategies concerning climate change. It is inevitable for the organizations to not think of a sustainable and efficient way for conducting business to make a positive impact on climate change. Although the concept of sustainability is not new, however, it needs to be evolved with respect to the innovation, changing times, and work style, accordingly.

With the announcement of Metaverse, the concerns about carbon emissions and energy consumption were also raised as the commerce of Metaverse is solely based on

cryptocurrencies. However, it has been highlighted by several studies that the Metaverse holds potential for reducing carbon reductions through virtual interactions, replacing physical with digital goods, and digital twins, respectively. Furthermore, it has also been suggested that Metaverse, through immersive experience, can help overcome behavioral hurdles concerning climate change.

Most of the studies use sustainability in the context of environment, however, sustainability should also be addressed from social point of view. Metaverse can help in enhancing social sustainability by bringing equity, inclusiveness, and accessibility on the table. It is the responsibility of the businesses and all stakeholders involved to develop strategies and utilize Metaverse for improving both the environmental and social sustainability, respectively. This section briefly discusses the correlation between sustainability and Metaverse with the use of Digital-Twins and Industry 5.0. The topics covered in this subsection are summarized in figure 16.

A. VIRTUAL RESOURCES IN METAVERSE

The core assumption and intuition of Metaverse being sustainable lies in the fact that it can use virtual and digital alternatives as a substitute for real-world experiences and physical goods. It is assumed that the virtual experiences and digital products will be carbon-efficient and less resource-intensive in comparison to their counterparts. A paradigm shift in terms of budget allocation from consumers have already been noticed that shows positive signs for a significant sustainability impact. For instance, Denim trade globally consumes 4.7 billion m^3 of water while emitting 16.0 metric tons of carbon dioxide equivalent (MTCO_{2e}) [244]. If consumers opt for a digital denim for their avatars instead of buying the physical one, it can save substantial amount of water and carbon emissions.

According to a study from EY Future Consumer Index³⁹ 21% of Metaverse consumers intend to buy digital items for their avatars in future rather than investing in physical items. The study [244] suggested that the transition to virtual denim from physical one can reduce the CO2 emissions by 10% which is equivalent to annual water consumption and annual emissions of around 350K internal combustion of automobiles in America [245], [246]. Considering that a digital transformation from a single product could impact the resource and carbon efficiencies in a significant way, it can be assumed that the Metaverse is a potential candidate to achieve the required environmental sustainability.

B. TRAVELLING THROUGH METAVERSE

Globally, air travel contributes to 2.5% of CO2 emissions but it was cut in half due to the COVID19 pandemic [247]. One of the earliest applications of Metaverse was to conduct a virtual meeting with a realistic VR experience. Recently, virtual concerts (Metaverse-based concerts) was organized which was attended by thousands of people in a virtual world [248] that indicates that both the business and recreational travel can be replaced by Metaverse to a certain degree. Furthermore, with such an immersive experience, companies and businesses can promote the work-from-home culture to cut CO2 emissions. Although, physical collaboration and personal presence is important and recreating a live gathering would not be as real in Metaverse as it is in physical world, we assume that the Metaverse is not here to completely replace it. Rather it can be considered as an effective tool to reduce complexity and expense of discretionary trips while maintaining environmental sustainability.

C. DIGITAL TWINS AND METAVERSE

Digital twins is the biproduct of emerging technologies such as AI, IoT, and augment and virtual reality. With the satellite generated data, digital twin can transform the real-world entities into virtual representations, hence propelling sustainability with respect to individuals, manufacturing assets, supply chains, and so forth. Digital twins and metaverse truly compliment each other with the specific characteristics. For instance, digital twins can simulate the interaction of company's information systems, equipment, and instruments in the digital world with the participants/avatars created through metaverse technology. Imagine a virtual training in which participants are from third world countries. All of the participants joined virtually do not have access to the representations of complex systems but with the help of digital twins the virtual participants not only can interact but also add value to the training. In short, the digital twin technology can empower the metaverse as suggested in [249].

It has been established by some studies that digital twin is one of the foundations for developing industrial metaverse [249], [250]. Furthermore, Global Lighthouse network

(GLN) released a recent white paper [251] also highlighted the importance of digital twins in attaining sustainability for industries, manufacturing, and production plants, respectively. Currently, there are many applications streamlined that use digital twins to improve the environmental sustainability. For instance, European space agency is working towards a system that can represent Earth's digital twin to study human activities and its impact on the climate. The simulation model will then be used for making policies to ensure the improvement in environmental sustainability. Similarly, using digital twin for supply chain and manufacturing can improve the optimization for logistics, traceability, energy, processes and material inputs, accordingly. Another example is that of LG Electronics, Republic of Korea, that used digital twin for simulating assembly line and performed its integration with real-time production to improve product quality by 70%, improve productivity by 17%, and reduce energy consumption by 30%, respectively. Similar example can be garnered from Procter and Gamble in China that improved warehouse operations by factoring in digital twin. The integration resulted in reduced logistic costs by 15%, inventory reduction by 30%, and improved the rate of delivery time, which currently stands at 99.99% [252].

Many industries have already started to adapt digital twin in order to reduce energy and scrap usage that contribute directly to environmental sustainability [253]. Digital twins have also been widely used for medical records, modeling data from wearable sensors and forecast individual's health with respect to air pollution and air quality [254]. However, the digital twins have achieved best environmental sustainability in the field of building operations that could help in improving space utilization by 25%, human productivity is increased by 20%, maintenance and operational efficiency has been improved by 35%, and lastly carbon emission for a building can be reduced by around 50%, respectively [255], [256], [257]. In recent interviews, Michael Jansen the CEO of Cityzenith (that is involved in making smart and sustainable cities throughout the world) has argued that urban digital twins and real-world Metaverse are synonymous and therefore, Metaverse would help in dealing with multisystem simulation and visualization of buildings and environment in digital space.

D. SOCIAL SUSTAINABILITY WITH METAVERSE

Most of the sustainability issues are centered towards its environmental aspect, however, Metaverse addresses the unsustainable social aspects of the physical world and coalesce social rights such as diversity, accessibility, and equity within its ecosystem. The same was recently highlighted by the Chief Diversity Officer, Maxine Williams by her statement "Diverse people shouldn't just participate in the Metaverse as consumers; they should be its architects and builders as well."⁴⁰ Recently, a bloomberg report [258] also

39. https://www.ey.com/en_gl/consumer-products-retail/future-consumer-index-moving-out-of-brands-reach

40. <https://tech.fb.com/ideas/2022/02/being-intentional-about-diversity-equity-and-inclusion-in-the-Metaverse/>

highlighted this issue concerning CryptoPunk NFTs stating that the digital avatar prices varied based on skin color, gender, and race, accordingly. Companies like OvalEdge⁴¹ have identified the problem as unconscious bias which is quite similar to the ones associated with AI models. The company suggest to use metrics and comprehensive set of target goals for the data scientist to reduce the bias and increase accessibility in Web3. Furthermore, stakeholders, civil society organizations, academia, investors, regulators, and businesses need to collaborate on this matter to make the Metaverse more democratized instead only decentralized.

E. SUSTAINABLE COMMUNICATION AND CONNECTIVITY

The fifth generation communication system was created with a lot of hype and ambition to bring ubiquitous connectivity to the users. In recent Mobile World Congress (MWC), vice president of distributed edge at VMware quoted that “5G is another phone in hands that is no different from LTE and 4G. The sixth generation communication system is about putting the focus back on humanity and sustainability.”⁴² The discussions on 6G always starts conversation in accordance to human, economic, and societal development. Furthermore, 6G emphasizes more on democratization instead of decentralization which is one of the major concerns with Metaverse and its coarse to sustainability. The sixth generation system is also being developed for achieving sustainability goals through better resource efficiency, less energy consumption, and less power requirement, accordingly. One of the driving forces for 6G advancement was the COVID-19 pandemic that made researchers and people realize about putting more emphasis on economic and societal needs of the broadband network instead of looking for nice presentation of devices and better performance. The 6G and metaverse are a good match for sustainable due to its characteristics of democratization and keeping human in the loop while breaking temporal and spatial barriers for multi-person communication.

F. METAVERSE SECURITY AND PRIVACY

Metaverse is simply a digital embodiment of the real world. However, Metaverse collects information from the user that is real to the physical world such as facial features, eye movements, hand movements, credit card details, address, name, and so forth. The collection of such information raises security and privacy concerns and might put the Metaverse user at risk. It is assumed by the experts that the Metaverse will be the prime target for the malicious actors and hackers for fraudulent processes. Additionally, Metaverse is also vulnerable to the spread of hate speeches and false information. A recent survey from Sprout⁴³

conducted from 300 marketers suggest that 64% of them are concerned about safety and privacy of the data concerning Metaverse.

Some of the recent studies have also highlighted the security, privacy, and ethical issues, concerning Metaverse. Pietro and Cresci [259] highlighted several security and privacy concerns related to Metaverse along with their logical implications. The study also provides several research directions to address security and privacy concerns related to the technical and non-technical paradigms for the realization of Metaverse. Zhao et al. [260] also highlighted the security concerns within the Metaverse ecosystem. However, the study divided the privacy and security concerns into four categories, i.e., Goods, Scenario, Communication, and user information. The goods in their study refers to the artworks, buildings, costumes, appearance, customized modeling of characters and personalized dress. Scenario is concerned with the religion, culture, and platform aspects. Communication reflects the understanding, mutual trust, cooperation, sharing, sociality, and interactivity aspects. Lastly, the user category considers the fusion of data acquired from multiple sensors and the collection of information. The information can be social, biometric, physical, or physiological, respectively. Gupta et al. [261] highlighted the privacy and security issues in the Metaverse in the context of service providers, stakeholders, technologies, and platforms. In addition, the study also provides ideas to handle security and privacy issues through the use of Zero-Trust Architecture and its integration with Metaverse system. Huang et al. [262] in their work, explored the expandability, real world-building, immersive interaction, and socialization characteristics of the Metaverse. While discussing the economic aspects of the aforementioned characteristics, the study also highlights the privacy and security risks including insecure design, broken authentication, data injections, phishing, unauthorized access, eavesdropping, and personal information leakage issues. The study also raised concerns related to humanity and society in the context of the Metaverse. Wang et al. [263] presented a systematic literature survey of studies carried out to address privacy and security concerns in the metaverse. In addition, the study aligns the security and privacy aspects with heterogeneity, sustainability, hyper spatiotemporality, and immersive realism, which are the main characteristics associated with the Metaverse. The study also delves into the potential research directions that could be helpful for coping with the security issues. Some of the prominent security, ethics, and privacy concerns in the Metaverse are highlighted below.

1) ETHICAL CONCERNS

One of the main ethical concerns in the Metaverse is related to the ownership and digital rights of the assets and creations that are built within the digital realm. Other ethical concerns include the accessibility and inclusivity of the individuals from diverse backgrounds so that they can participate in the

41. <https://www.ovaledge.com/>

42. <https://www.trendingtopics.eu/how-will-6g-and-the-metaverse-change-the-world/>

43. <https://sproutsocial.com/insights/metaverse-dangers/>

Metaverse with equal rights. One of the concerns regarding inclusivity is that of cyberbullying and virtual harassment, which needs to be addressed in the Metaverse ecosystem. Lastly, the fairness and algorithm biases concerning the methods and platforms used for the creation of digital realm in Metaverse needs to be responsible for avoiding any user discrimination.

2) VIRTUAL THEFT

Similar to the economic system and applications in the real world, virtual world is also vulnerable to hackers and thieves that are looking to target the assets such as virtual currency, rare virtual items and virtual real estate, in the Metaverse. The malicious users can exploit system vulnerabilities to perform the virtual theft. Therefore, securing the virtual assets needs to be addressed within the Metaverse before its realization.

3) SOCIAL ENGINEERING

In real world, the tactic to convince an individual for revealing their sensitive information is referred to as social engineering. The same tactic can be exploited convincingly with the persuasive interactions and design of avatars. Such tactics by hackers can be used to make the user reveal their identity, financial, or personal information, which could lead to any form of losses.

4) MALWARE ATTACKS

In digital world, the hackers or malicious users can pass on the links to malicious softwares and viruses, which can put not only their digital footprint but also the information in the physical world at risk. Furthermore, the click to the links in virtual world while interacting with the digital objects is quite ubiquitous and persuasive in comparison to its physical counterpart.

5) DATA BREACH

Data breach issue is one of the most prominent ones in the physical world, therefore, Metaverse will be implicitly vulnerable to such an attack making it the ground zero for attackers and hackers. Hackers trying to gain access to your personal photos, and information via the virtual platform needs to be addressed before the large scale realization of the Metaverse.

6) DECENTRALIZATION

One of the highlights of the Metaverse is that the ecosystem is decentralized suggesting that no central authority is incharge for the control and regulation of virtual environment. It allows the users with high degree of autonomy and freedom. However, the same characteristics can also be used for causing harm to the users as there is no accountability or oversight to the content being created, posted, or shared.

VII. METAVERSE APPLICATIONS AND USECASES IN GENERAL

A. WHAT ARE THE USE CASES OF THE METAVERSE

1) METAVERSE AND PHYSICAL WOLD: HOW DO THEY INTERACT

To understand the different uses of the Metaverse, one must first know what it is. Users can interact with varying spaces as their digital avatar in the Metaverse, an immersive 3D virtual world. Metaverse users can move around different areas as their digital avatars, just like they do in the real world. Users can also create, share, or trade experiences and assets using the Metaverse [54]. Recently, the proverbial Metaverse was rumored worldwide, and people are taking a great deal of interest in its use cases. Many companies, such as Facebook, noticed it unveiled Meta as the brand name of their parent company at the Facebook Connect event in late October 2021. Social media giant Biggie has recently launched Metaverse tools for developers as well. There are three components to it, including a Headset, Presence Platform, and developers' AI toolkit. The interaction of VR/AR objects with users can be programmed. Similarly, Microsoft has invested in Metaverse to create an environment that fosters collaboration with Microsoft Mesh. Almost all major tech companies have jumped aboard the Metaverse bandwagon, doubling the demand for Metaverse use cases.

B. USECASES

Having a basic understanding of the Metaverse and why it is gaining popularity, you must be looking forward to discovering its use cases. Since the Metaverse is cutting-edge technology, many people wonder, "What are the benefits of a Metaverse?" In what ways will you use the Metaverse to your advantage? What roles will digital reality play in the real world? From identity verification to payments, the world around us has become more and more digital [264]. In turn, a digital world like the Metaverse makes it possible for individuals and businesses to change how they view and use technology. Below are some examples of how the Metaverse could be used [1], [265].

1) UNLOCKING MARKETING PROSPECTS

A possible use case for Metaverse would be the possibility of unlocking new marketing opportunities [36]. People can interact with digital avatars to do many things in the virtual world. Furthermore, people engage in the Metaverse's socializing, leisure, and learning activities. Marketers could take advantage of exclusive marketing opportunities in different virtual worlds in the Metaverse. Marketers have already taken advantage of in-business opportunities in the Metaverse. Such as Anzu, which uses ads to track real-time views in gaming environments across mobile and console platforms. Also included in this list are brands like Paramount and WarnerMedia. In the Metaverse, the ads are reminiscent of real-life, and they are intertwined with the gameplay, where the ads can be found at the right places. For instance, billboard ads or characters wearing branded

clothing offer promising brand exposure. Metaverse games have proved how Metaverse can open up new marketing prospects [266].

2) BLOCKCHAIN USE CASES

Blockchain applications could provide advanced technology as the most prominent use case in the Metaverse [6]. Decentralizing the Metaverse through the adoption of large-scale Metaverse across various industries is a powerful foundation for the large-scale Metaverse. Blockchains enable the development of dApps and NFTs, power cryptocurrencies, and function as a distributed ledger for recording peer-to-peer transactions. Blockchain technology offers several benefits for engaging the NFT marketplaces fostering new and realistic avenues [267]. Users can communicate with other users and share more interactive Metaverses in the NFT marketplaces. Users can interact with NFTs to make informed purchasing decisions via the Metaverse. Metaverse blockchain application cases include the promotion of new NFTs or the development of a shared virtual area. The blockchain-based games trend has attracted a great deal of traction. Players in NFT or blockchain games can gain various in-game collectibles to exchange with other players or on external marketplaces. The Metaverse can power Blockchain-based online gaming [42].

3) VIRTUAL TOURISM

Virtual tourism is another promising use case of the Metaverse [268], [269]. The development of advanced technologies has led to the point where one can enjoy traveling without physically reaching the destination. There is a big difference between experiencing such destinations in person and watching them on video. The Metaverse could be used to create immersive digital environments through virtual reality (VR) [59], [60], and augmented reality (AR) [61], [62], [63]. You may stir your audience's imagination by merging immersive digital reality with real content. As a result, people can experience their environment as physically present. The possibility for widespread adoption and acknowledgment of VR tourism is a possible mainstream use case. There is an increasing amount of 360° video content on video streaming platforms such as YouTube and other content hosting services. A serious drawback of using Metaverse for virtual tourism is its limited freedom, as you can notice with the use cases. Tourism destinations are not flexible enough to allow people to move around since they can only be viewed recorded.

4) WEB REAL-TIME COMMUNICATION

A Metaverse can also facilitate real-time communication in Web experiences, based on the search for blockchain use cases in a [51]. A real-time communication initiative for mobile applications and Web browsers is known as real-time Web communication. One of the most intriguing applications is the Metaverse to transform traditional audio and visual communication. You can transfer information between clients

through real-time Web communication without requiring an intermediary server. Thanks to peer-to-peer communication in the Metaverse [270], direct communication between browsers could become possible. In addition to providing a platform for designing new Web communication standards, the Metaverse technology offers an intriguing application case. Web real-time communication can also be combined with numerous media streams, which is important for constructing virtual worlds.

5) VIRTUAL OFFICE AND LEARNING SPACES

Remote working grew as a result of a global pandemic. The pandemic exposed professionals from various sectors to Skype calls, Microsoft Teams, and Zoom meetings. Remote professionals were able to communicate virtually with these tools [271]. Metaverses offer many possibilities for developing virtual office spaces or learning environments [272], [273]. Working or learning together in the Metaverse is possible if you feel like you are in the same room. Virtuworx, for example, has created virtual office spaces by leveraging Metaverse use cases. With its hybrid of virtual and mixed reality environments, the company offers a meaningful and productive work environment. Team members can access various functions such as events, offices, conferences, virtual training, and trade exhibitions by using a completely configurable solution. Metaverse benefits are found in the education sector as well. Minecraft and Second Life have been used to improve student learning experiences in universities. Students in architecture and medicine may also benefit from VR simulations in the Metaverse.

6) AI-POWERED HEALTHCARE SIMULATIONS

AI-powered healthcare simulations represent a transformative paradigm in medical training and education within the Metaverse. In this context, artificial intelligence serves as a catalyst for revolutionizing how healthcare professionals are trained, honing their skills in realistic, virtual environments [274], [275]. These simulations harness the capabilities of AI to create immersive and dynamic scenarios, replicating a diverse range of medical situations with precision and detail. One of the key advantages of AI-powered healthcare simulations is their ability to provide a safe and controlled environment for practitioners to practice and refine their skills. Healthcare simulations within the Metaverse utilize AI-driven diagnostic tools for training medical professionals. Simulated scenarios, powered by AI, replicate real-world medical situations for immersive and effective training. With 6G's low latency and high reliability, healthcare professionals can conduct remote consultations within the Metaverse, providing medical services and expertise globally.

7) SMART CITIES AND URBAN PLANNING

In the Metaverse, AI algorithms analyze data from smart sensors embedded in cities to optimize traffic flow, energy consumption, and public services [84]. This supports efficient

urban planning and resource management. 6G networks facilitate seamless connectivity for the Internet of Things (IoT), enabling a multitude of sensors and devices to communicate and share data for smart city applications.

C. PENETRATING PSYCHOLOGICAL BARRIERS THROUGH METAVERSE

It has been suggested by many studies that environmental sustainability and climate change are highly correlated. Companies and industries might have the power to slow down the carbon emissions, however, the masses or general public can be equally held responsible for using the items that are not ecological friendly. Although, past years have recorded around two billion social media posts that address the climate conditions but a recent study showed that the general public bases their idea of climate change with respect to normal weather, therefore, their perception is quite short-term, i.e., the affect that started to come in play since 2 - 8 years [276]. The use of Metaverse for providing immersive experience and simulation of climate change can tap into consciousness of general public to spur the action towards usage of eco-friendly products, hence, reducing the carbon emission footprint. The relationship of virtual reality and climate change psychology has been carried out and addressed in a recent study by Marowitz [277] to compel the general public for opting proenvironmental actions, respectively.

D. BENEFITS OF METAVERSE

It is equally important to know the benefits of the Metaverse after understanding its use cases. In the different examples of how a Metaverse might be used, an impression can be gained of its potential advantages [3], [270]. As technology advanced, it answered many uncertainties like who would have imagined that people could make video calls over long distances to share data in seconds. If someone wondered about the benefits of the Metaverse in the past, you might not have found many answers, but at the moment, they seem evident to everyone. However, virtual spaces and digital communication avenues are used by millions of people worldwide to socialize remotely. Beyond adding real-world capabilities to virtual worlds, Metaverse has several benefits for the digital world. Here are a few of the Metaverse technology's key advantages.

1) INNOVATION IN HEALTHCARE

To understand how healthcare sectors fit into the Metaverse, we need to examine their promising benefits. For example, the Metaverse provides a unique opportunity for patients to interact with healthcare professionals regardless of their geographic location [275]. Healthcare professionals can interact with patients in virtual worlds in real-time through the Metaverse. In addition, medical students can engage in engaging and comprehensive learning experiences through virtual reality simulation in the metaverse [274].

2) METAVERSE AND EXCITING NEW GAMES

The Metaverse will play a crucial role in gaming applications through play-to-earn models, which enable developers, publishers, and users to reap economic rewards from gaming experiences [266], [278]. On different online marketplaces, gamers can, for instance, create and trade in-game assets. Thus, the benefits of decentralization inherent in blockchain combined with Metaverse can revolutionize gaming.

3) COMPLETELY NEW ECONOMY

One of the most prominent assumptions about the Metaverse is the possibility of a creator economy. Trading assets across different spaces is made possible by the Metaverse [279], [280]. On another platform in the Metaverse, you can sell an NFT you created in a Metaverse game. A great deal of economic growth can be attributed to DeFi, NFTs, and blockchain games.

4) ENVIRONMENTAL IMPACT

The metaverse facilitates the creation of virtual workspaces and offices, presenting a tangible opportunity to cut down on physical office environmental impact [281]. The reduced demand for sprawling buildings translates into lower energy consumption, as the virtual realm thrives on digital infrastructure, bypassing the need for extensive physical structures in traditional office settings. The metaverse is not only a realm of virtual experiences but also a potential catalyst for environmental awareness. Educational initiatives within virtual spaces, such as simulations and interactive content, have the capacity to inform and inspire users to adopt environmentally conscious behaviors and lifestyles [282]. As the metaverse evolves, it stands as an alternative to physical events and conferences, minimizing the ecological impact associated with constructing and maintaining large venues. Virtual gatherings provide a greener solution, aligning with a global shift towards more sustainable practices in the face of environmental challenges. In essence, the metaverse holds the promise of fostering a digital ecosystem that is not only innovative and immersive but also environmentally responsible. By harnessing the potential of virtual spaces, we have the opportunity to create a more sustainable and ecologically conscious future.

E. METAVERSE MARKET: STATE OF THE ART

Without reflecting on the state of the current Metaverse, many people are intrigued by the question, "is the Metaverse the next Internet?" What number of projects are currently being developed? Is the Metaverse attracting attention from big names? Take Facebook, for example. Can we expect other tech giants to pay attention? There must be multiple organizations, creators, and developers creating the Metaverse, no matter who owns it. Metaverse adoption will also be mainly determined by its names. These are some of the top companies that have begun to develop a Metaverse [283].

TABLE 9. Ongoing Metaverse projects.

Project Title	Project sub-title	Project Length	Project URL
Decentraland	Virtual advertisement for content, goods and services	2015 - ongoing	https://decentraland.org/
Oculus (Meta Quest)	Meta's Metaverse platform - VR equipment, experiences and games	2014 - ongoing	https://store.facebook.com/quest/
Enjin	NFTs for everyone	2009 - ongoing	https://enjin.io/
Silks	Horse racing and bidding in Metaverse through NFTs	Upcoming (2022 - 2023)	https://silks.io
University of Miami - XR initiative	Multiple XR and Metaverse based projects	2018 - ongoing	https://xr.miami.edu/projects/index.html
MirageXR	Learn through holograms	2021- ongoing	https://wekit-ecs.com/team
Highstreet	Metaverse shopping and product showcases	2021 - ongoing	https://www.highstreet.market/
Metahero	3D scanning of humans to create their own NFT avatars for Metaverse	2021 - ongoing	https://metahero.io/

1) FACEBOOK

Many tech enthusiasts have viewed Facebook's Metaverse announcement as a PR stunt. It is crucial to consider how a tech giant like Facebook can help create a more promising market for the Metaverse. Furthermore, Facebook has almost all of its resources to develop the Metaverse, from infrastructure to human interaction to discovery [284]. The online networking behemoth has a massive advertising engine, Oculus headsets, and a burgeoning creator economy.

2) EPIC GAMES

Epic Games, a well-known game production studio, competes for high positions in the Metaverse's future. Epic Games co-founder Tim Sweeney outlined a vision for the Metaverse a few years ago, and now the firm has the appropriate platform for it to thrive. Epic Games can potentially grow Metaverse growth with 1 billion dollar in funding from Sony in the future [285].

3) ICROSOFT

Microsoft's efforts to develop the Metaverse cannot be ignored under any circumstance. The involvement of companies like Microsoft assuages concerns about the Metaverse's future. Microsoft is constructing Microsoft Mesh, a business-focused Metaverse [286]. Users would be able to connect to Microsoft products through a digital environment seamlessly. Using Microsoft Mesh, users can leverage Windows, Teams, and other services through VR.

4) DECENTRALAND

Decentraland is an example of the resiliency of the Metaverse market. Metaverse is one of the first pioneering products that explicitly mentions the Metaverse. Users can trade in virtual real estate and create NFTs on Decentraland, developed in 2017. A recent auction in Decentraland featured virtual real estate worth more than 2 million [287], [288]. This means Decentraland is likely to become one of the top names in the Metaverse of the future. Microservices and blockchain technologies are also included, along with edge computing and AI agents.

VIII. PROJECTS

An interconnected network of 3D virtual worlds is one way to define the concept definition of the Metaverse. Through a virtual reality headset, users enter these worlds, navigating the Metaverse with their eye movements, feedback controls, and voice instructions. The user is submerged by the headgear, producing a phenomenon called presence, which is achieved by simulating the genuine physical experience of being present. But before the Metaverse is widely and universally adopted, there are obstacles to be resolved. The virtual aspect of this environment is a significant obstacle. Although a VR headset is often required for entry into the Metaverse, this is not the only need. It is expected that the Metaverse industry will overcome these challenges as there is a tremendous growth in the sales of headsets supporting Metaverse concepts.

There are many players entering into the Metaverse universe in the recent years. The few significant ongoing Metaverse projects are shown in Table 9.

A. DECENTRALAND

Decentraland is a decentralized blockchain-based Metaverse. Decentraland focuses on creating, exhibiting, and selling real-world and NFT assets. Decentraland is governed by a Decentralized Autonomous Organization (DAO), which owns the necessary smart contracts based on which Decentraland operates. Users can vote using the DAO system to influence the various aspects of the Metaverse. The assets can be bought using multiple currencies, such as polygon and ethereum, while the parcels of land on the Metaverse can be purchased only using ethereum.

Major brands such as Samsung, Atari, and Adidas have bought plots of land in Decentraland and established their products' showcases. The various brands in the Decentraland perform live events and immersive experiences. For example, Samsung recently hosted a live event of their Galaxy S22 unveiling in the Decentraland.

B. OCULUS

Oculus is the online platform that holds the experiences and games accessed through Meta's VR headset platform

(Quest). Though it is not a Metaverse of its own, it provides a variety of backgrounds and games that can be experienced through the headset. The significance of Oculus is that it serves as the ground for Meta's future planned expansion into the Metaverse concepts. Hence, it is vital to closely monitor the developments in Oculus even though it is not a Metaverse yet.

C. ENJIN

Enjin is a marketplace and platform that deal with the creation of NFTs for Metaverses. The Enjin provides Software Development Kits (SDKs) that support these activities. Enjin works with two different types of currencies - Enjin token and Enjin coin. Furthermore, they provide integration support to integrate the trading of the created NFTs inside your Metaverse applications. Examples of Metaverses running on Enjin platform are AlterVerse, MotoBloq and Division Network. Enjin also actively funds Metaverse projects and such projects can apply for funding through their website.

D. SILKS

Silks, a game platform for the Metaverse, mimics the thoroughbred horse racing industry in real life with the use of a blockchain-enabled Metaverse. A play-to-earn gaming economy powers the Silks Metaverse, enabling people to own racehorses and horse farms while earning tokens via skillful games and contributions to the Silks ecosystem. The users will be able to purchase, gather, exchange, and interact with digital assets that reflect genuine thoroughbred racehorses. Users will also be able to buy, build, and maintain horse farms, other real estates, and interactive digital assets. The project is underdevelopment and is expected to be fully functional by 2023.

E. XR INITIATIVE

XR initiative is a initiative from Miami University to explore use cases of XR and VR and their interoperability. The XR initiative is significant since it focuses on non-gaming domains such as education and healthcare. Though the XR initiative is not a complete Metaverse of its own, the various projects provide a possible look into the utility and usecases of Metaverse in the future. The projects part of this initiative include anesthesia training for nurses and technological training for persons suffering from autism spectrum disorder.

F. MIRAGEXR

MirageXR enables educators and developers to create unique holographic training programs, enhancing workplace efficiency, enabling data analysis to evaluate performance, and assisting industrial organizations in saving money on training expenses. The app's core is technology-enhanced learning, which helps users go beyond simply remembering and comprehending the content of learning exercises by actually performing the action themselves.

The project's authoring and performance analytics capabilities allow AR course designers to update activities, gauge

engagement quickly, and assist learners in analyzing their actions by recording practice sessions to enhance practice.

Recently, with the growth of AI, large language models, emerging communication technologies, startups and projects are starting to emerge that focus not only on the green economy circular system but also healthcare, networking, building communities, real estate, and transportation. Following are some of the projects that help in building a societal impact through Metaverse.

1) VREALTY

This is a metaverse-based real estate project that allows the buyer to showcase their properties through virtual tours, while the buyers can interact with the property and items in the digital world to gain an immersive experience before taking a decision to invest in the property. The technology saves on waiting period for viewing the property as well as help the buyers to save conveyance expenses, accordingly.

2) METAMED

The project revolves around the service provisioning concerning medical and healthcare within the Metaverse ecosystem. The project provides health-related applications, virtual clinics, and telehealth services, especially the tele-radiology services. The said technology pools specialists for its operation across the region and provides round the clock services with highest quality. Furthermore, they provide medical and healthcare consultancy services in the digital space.

3) METADRIIVE

This project⁴⁴ is focused on the digital transformation of autonomous driving. The project leverages AI, specifically the use of reinforcement learning (RL) to map various traffic scenarios, road maps, and scenes for the simulation in digital realm. The simulation includes first-person view images, semantic maps, RGB images, Lidar with other sensory inputs and accurate physics simulation. The environment can be used for testing the performance efficiency of self-driving cars or refine the performance of autonomous vehicles for a particular environment and terrain.

4) METASPORTS

This project facilitates the sport industries in various ways such as training, simulations, digital tournaments, sports events organization, and so forth within the Metaverse ecosystem. The players can immerse themselves in training while the fans experience real-time interaction with the sports being played out live in real-world.

5) VERIZON METAVERSE LAB

Verizon is exploring the Metaverse paradigm by leveraging AI and 5G technology to enhance user experience in the digital realm. The project provides a firm platform to the

44. <https://github.com/metadrive/metadrive>

Metaverse developers for designing solutions concerning healthcare, fashion, real-estate, and entertainment that are compatible with high-speed networks.

6) VEYOND METAVERSE

Veyond Metaverse has been a leader in healthcare technology when it comes of eXtended reality (XR). Veyond Metaverse has been listed as one of the best emerging startups for Metaverse. The platform leverages the power of VR, AR, and XR to provide education and interactions to the users and students with respect to surgical instruments, surgery scenarios, and healthcare services, respectively.

7) EDVERSE

Edverse is basically educational metaverse that provides the services of alumni meetups, virtual classrooms, and joining classes using blockchain technology such as Elysium and Polygon. The educational library is transformed as assets in the form of NFTs, which not only incentive the stakeholders but also the students through token earning.

G. HIGHSTREET

A Metaverse with a focus on business. Web browsers can be used to access the market. The Metaverse promises possibilities to interact with famous people who will introduce their brands on the Highstreet. There are face-to-face interactions available in the Highstreet Metaverse. The Highstreet is home to a unique cryptocurrency lounge where customers may exchange digital currency in a virtual reality setting. Every item sold on Highstreet is displayed to the customer in both digital and physical forms, connected via a product token. In addition to being able to wear a pair of shoes the user purchases in the real world, they may also be added to their avatar's wardrobe in the Metaverse.

H. METAHERO

The Metahero project employs NFT smart contracts and 3D scanning technologies to enable the development of unique meta avatars and meta-objects. Metahero's fundamental technology is 3D scanning, which examines physical objects to gather information about their appearance and digitally depict them. Wolf Studio and Metahero have a partnership for 3D scanning. The concept of Metahero is to scan the user's body using 3D scanning machines and then create realistic NFTs. These NFTs will be utilized as the users' avatars inside the Metaverse. The project is in the development stage, where the users can sign up to be notified if a scanner is available near their location.

IX. LESSONS LEARNED

Based on the systematic review and tutorial like information presented in previous sections, the practical lessons and recommendations are as follows:

1) ART AND IMMERSIVE EXPERIENCE

A continuous advancement has been recorded in the field of AI, let it be in the form of self-supervised learning, explainable AI, generative adversarial networks, variational autoencoders, transformers, or large-language models [113], [114], [116]. All of the aforementioned methods have been used in some capacity or another to make the visualization of images/frames better and unique. Recently, large-language models such as Dall-E2 [115] has taken the Internet by storm with the creation of realistic images via language understanding. It will help not only with the creation of scintillating art but also unique visual experience for the users.

2) CIRCULAR ECONOMY

In simple words, circular economy is all for producing waste and circulating materials and products in order to preserve nature. Although many companies have move towards eco-friendly products but the impact is not substantial. We have discussed as to how the travel reduces CO2 emissions. In 2017 alone, the conference and exhibition industry was estimated to be 2.5 trillion dollars of worth, which requires substantial travel. Metaverse can help reduce the air travel by making the exhibition and conference industry digital/virtual, which will not only help in achieving sustainable development goals but will also help in cost savings for both the parties, hence a more circular approach [289]. Similarly, a game could be designed that can motivate the consumers for not using plastic items and using recycled products for minting a fraction of a coin (mining approach).

3) SUSTAINABILITY IN METAVERSE

It has been suggested by researchers as well as industry personnel that Metaverse can help in improving overall sustainability [290]. It can be the motivation for users to opt for digital clothing, virtual concerts, virtual meetings, and so forth. If used the right way, achieving sustainability through Metaverse would be inevitable. However, it could be used otherwise to disrupt the sustainability goals, therefore, regulations, guidelines and laws needs to be made and enforced for making the Metaverse a savior. Furthermore, the use of digital twins has already proven to be a positive way towards sustainability. In addition, the Metaverse also need to work on social sustainability so that the virtual system could achieve democratization instead of only moving towards decentralization.

4) LAYERED SECURITY IN METAVERSE

Metaverse is without a doubt a game changer but with the increasing number of users, it will also be a nightmare for security personnel. It is estimated that cyber crimes would increase manifold as the Metaverse move toward commercialization. For instance, a successful business deal can turn to a disaster if the avatar (person) is impersonating someone else. Therefore, a layered security will be essential to secure the data as well as AI methods in Metaverse.

Emerging technologies such as Federated learning, Private AI, and Blockchain along with encryption and privacy-preservation methods would be used to maintain security in Metaverse ecosystem [291], [292].

5) WIRELESS INTERACTIVITY IN METAVERSE

The previous generations of wireless communication systems have concentrated mostly on improvement of connectivity. However, the future generations of mobile terrestrial systems will be blending connectivity with virtual and physical space, as well as ubiquitous intelligence. There is a potential for the wireless interactivity, which is made possible through future communication technologies, to play an important role in the establishment of links between cyberspace and physical space, as well as among humans. THz communication will be particularly useful for ultra high data rate communications within short distances that have absolutely zero error rates, as well as high data rates [24], [26], [27]. Moreover, in the near future, AI will have a huge impact on the future of 6G-powered wireless communications by becoming both native and ubiquitous, which will enable all the components of 6G to be intelligent and user-friendly. As the Metaverse grows, 6G is also likely to be dominated by an increase in interactivity, which will be one of its key fundamentals [293]. 6G-based interactivity will provide Metaverse users with multi-sensory experiences that are immersive and tactile, hence enriching their daily lives and enhancing their quality of life.

6) DIVERSE SERVICE REQUIREMENTS IN METAVERSE

It is possible that the mobile networks will not be utilized to their full potential due to the diverse and sometimes conflicting requirements of the various Metaverse services and applications. In such cases, 6G networks allow slicing of the network into multiple virtual and standalone logical networks while sharing a same physical infrastructure [193], [294]. Thus, each network slice can be customised to serve a Metaverse application in an efficient way by taking care of the energy efficiency, latency, dense connectivity, mobility, and bandwidth. A key feature of 6G networks will be the provisioning of network slices in a dynamic manner [190]. Rather than categorizing Metaverse applications into eMBB, mMTC, and URLLC as in the traditional networks, 6G networks will be capable of providing dynamic types of service depending on the network traffic and the user requirements.

7) SELF-SUFFICIENT INFRASTRUCTURE IN METAVERSE

Existing communication and computing infrastructures are limited in terms of scaling the services and applications according to dynamic requirements. As an example, Facebook space (a VR-based social network), is only able to handle a maximum of three people to socialise in the environment it provides. Metaverse will bring many essential use cases for which this is inefficient, including virtual classrooms, holoconferences and events, and

virtual tourism [3], [295], [296], [297]. With the advent of decentralised intelligence, multi-access edge computing, microservices, and reinforcement learning techniques, a ray of optimism shines through the way for such immersive applications [10], [34], [40], [198]. A Metaverse environment supported by 6G networks will be made more responsive by automating the wireless networks with advanced deep learning methods. In particular, 6G combined with the incredible capabilities of reinforcement learning has the potential to truly transform the existing infrastructure and making them suitable for Metaverse environments. Moreover, implementing AI as a native function of the network will enable 6G to become the first-generation network to promote large-scale deployment of self-optimized and automated networks [21], [298]. As a result of the latest advances in aforementioned technologies, practices, and methods, the future wireless networks will be able to co-exist according to their state and achieve the goals set for them.

X. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

This section discuss and enlist the foreseeable challenges and future research trends concerning the role of AI, B5G/6G, and their interplay in Metaverse.

A. ROLE OF AI IN METAVERSE

This subsection highlights foreseeable challenges and future directions concerning the role of AI in Metaverse.

1) INTEGRATION WITH EMERGING TECHNOLOGIES

It is apparent from the growth of Metaverse that more and more users will explore and adapt to the aforementioned technology. In order to handle scalability, Metaverse needs to integrate with emerging technologies such as 5G/6G, Industry 5.0, Internet of Aerial and Ground Vehicles, and so forth. The repercussions or issues that may arise from such integration are yet to be seen but we can assume that the heterogeneity, bandwidth management, energy efficiency, and security would be a few of them.

2) UNIQUE IMMERSIVE EXPERIENCE

Metaverse is known for realistic and immersive experience in digital world. However, as the marketplace gets saturated, the users will demand for unique aspects such as new digital landscapes, more interactive spaces, experiences based on reality, and real-time emotion mapping in digital world. Few of the aforementioned issues can be handled by large language models and methods like Dall-E, but these models and methods are not publicly accessible. Furthermore, the usage of these models cannot be handled by hand-held devices, therefore, the challenge of designing platforms that could provide mutual services and solutions will be in dire need.

3) DEMOCRATIZATION

From the review of seminal works, it has been revealed that the Metaverse is far from being democratized at this point. With the growing and diverse users, Metaverse will have to opt for democratization in order to maintain sustainability. Researchers have suggested to use AI-based smart contracts to detect anomalies, but that is yet to be achieved, and the outcomes are yet to be realized. AI is itself subjected to biases, therefore, humans in the loop for making the process of democratization bias free needs to be integrated.

4) INTELLECTUAL PROPERTY PRESERVATION

Metaverse has been mainly introduced as an extension of our reality. This extension brings forth the businesses challenges that exist in the real-world such as brand protection, copyright issues, theft of intellectual property and more. Due to being in a digital space, the counterfeiting in Metaverse would be much easier, and reproducibility of the trademarks in the form of virtual images or NFTs would be much cheaper. The challenges for this category are not only related to AI, but also the law enforcement agencies and intellectual filing offices. Furthermore, methods needs to be devised to confront anonymity in the Metaverse as it will hinder the most for content and brand owners to enforce their intellectual property rights.

B. ROLE OF B5G/6G IN METAVERSE

This subsection highlights foreseeable challenges and future directions concerning the role of B5G/6G in Metaverse.

1) MASSIVE, HIGHLY DYNAMIC, AND COMPLEX METAVERSE

It is beyond question that Metaverse will be build on top of the highly dynamic, massively dense, and exceptionally complex mobile networks. These networks will be composed of ultra-large scale and inherently heterogeneous equipments. There are, however, many features that are fixed in the architecture of current wireless networks, and the optimization tasks are thus defined to address particular challenges and services that have been identified and defined in advance [299], [300]. Consequently, the existing process of manually optimizing and configuring networks is not suitable for the Metaverse. Further, the original 5G service classes will be challenged by new immersive experiences such XR gaming, teleoperations, and holographic telepresence that will become available soon in the context of Metaverse [301]. Therefore, future mobile networks have to simultaneously deliver high transmission rates, high reliability, and low latency in order to effectively provide aforementioned Metaverse services.

2) ZERO-TOUCH MANAGEMENT FOR METAVERSE

Future wireless networks for Metaverse will not rely on manual interventions to avoid any minacious possibilities. Hence, ZTM will play a useful role by controlling, monitoring, and configuring the tasks for massive networks

Meta-Immersion			
Experience Factors	Feeling of Presence	Feeling of Interaction	Feeling of Pleasure
Service Indicators	Resolution Frame Rate Refresh Rate Jitter Motion Blur	Tracking Sensor Buffer Time Operation Delay Response Time Postural Stability	Cybersickness Sensory Mismatch Nausea Scale Six Degrees of Freedom Number of Motion Axes
Relationship			
Technical Indicators	Downlink Data Rate	Uplink Tracking Bit Error Rate	Virtual Experience
Minimum Requirement	2160×1200@90fps; 20–38Mbps 2560×1440@60fps; 22–42Mbps	10 ^{−5}	

FIGURE 17. Some KPIs and requirements for evaluating the immersiveness in a Metaverse environment [304].

to attain a fully independent closed-loop automation by alleviating any opportunities of human intervention [221]. In current wireless networks, ZTM has been enabled for specific 5G/6G usage scenarios [223]. However, Metaverse will expose diverse requirements occurring from heterogeneous user application. Hence it demands for a universal ZTM strategy to meet the requirements of several verticals in Metaverse.

3) SPACE-AIR-GROUND-SEA COVERAGE FOR METAVERSE

The space-air-ground-sea integrated communication network will empower Metaverse in two folds:

- Non-terrestrial networks will provide ubiquitous wireless access to users from anywhere at anytime [302].
- Terrestrial networks will support Metaverse users to hop freely among space-air-ground-sea intergrated networks for an uninterrupted immersive experience [30], [303].

However, the highly frequent fidelity of momentous data among space-air-ground-sea can cause significant delays requiring massive bandwidth and overwhelming backhaul resources [172]. Thus, it becomes imperative to explore new SAGSIN architectures and simulation platforms to underpin the diverse and extensive services and applications of Metaverse. Further, reliability could be compromised in existing SAGSIN architectures due to highly mobile nature of satellites which may eventually cause disruption to Metaverse applications. Hence, novel reliability evaluation metrics are needed to be designed for future services of Metaverse, as proposed by researchers in [304]. Figure 17 shows some of the requirements for seamless meta-immersion and indicators to evaluate the performance of services.

4) TACTILE FEEDBACK IN METAVERSE

It has been discussed in Sections IV-D and V-C that certain applications of Metaverse, such as robotic surgery, avatar-to-avatar interaction, teleoperations, and telepresence need to rely on every tiny bits of tactile information occurring from the interaction between physical and meta environment

in order to function normally. Although IEEE introduced a standard for tactile Internet (IEEE P1918.1) to normalize such activities, however, the requirements of tactile feedback are ultra-low latency such as in milliseconds [225]. The existing 5G-URLLC usecases are expected to meet these requirements. Irrespective of that, the tactile Internet poses a number of potential research challenges that have yet to be fully addressed, particularly in the context of Metaverse. For example, efficient routing and MAC protocols for delivering tactile information can be proposed for Metaverse usecases [305]. In addition to that, intelligent and adaptive network traffic management can be explored for delivering multi-sensory audio-visual tactile information over wireless networks. Lastly, the computing capabilities can be accelerated for immersive services by apply compression techniques as pro-processors for tactile information.

C. INTEGRATED ROLE OF AI AND 6G IN METAVERSE

This subsection highlights foreseeable challenges and future directions concerning the integrated role of AI and 6G in Metaverse.

1) 6G-ENABLED EDGE AI IN METAVERSE

It is anticipated that Metaverse will bring a complete shift of AI from cloud to the network edge, hence achieving on-device intelligence for Metaverse services. Edge AI can certainly benefit Metaverse in achieving low latency response while ensuring privacy of the user's data [38], [203], [293]. However, the offloading of Metaverse services will pose severe challenges for the existing wireless networks. For instance, Metaverse users based in remote regions with poor Internet connectivity might face a disconnect due to high latency. For mission-critical applications, this latency can potentially lead to worse consequences. Hence, modern communication systems can leverage 6G-uMBB services to support Metaverse applications on the end devices [306]. Edge caching can also be explored to further reduce the transmission latency. Furthermore, Metaverse will enable collection of sheer amount of heterogeneous data (due to diverse users/services), hence edge devices can leverage the federated learning to perform model training locally without violating any privacy laws as shown in Figure 14.

2) AI-BASED NETWORK AUTOMATION FOR METAVERSE

In a Metaverse composed of heterogeneous users and services, the network automation will be of key importance for delivering seamless QoE to users. AI has to play a vital role in enabling self-adaptive capabilities in 6G networks. Recently, AI-based frameworks have been widely used for empowering automation in 6G networks by allowing them to self-allocate, self-configure and self-optimize the network equipment and resources [222]. However, as anticipated in Metaverse, these abilities can be hindered by following challenges when leveraging AI:

- Lack of labeled training data to update the AI model given the changing context

- The complexity of underlying deep learning models to be ported on resource-constrained devices
- The limitation in availability of hardware to support new and emerging intelligent services for Metaverse

To address the aforementioned challenges, the possible research directions would be to adapt self-supervision learning techniques for training AI models, and distributing the AI models in the end-edge-cloud continuum to alleviate the computational load on end/edge devices.

3) ENERGY EFFICIENT AI AND 6G FOR METAVERSE

Energy efficiency will remain amongst key KPIs for Metaverse developers when proposing AI and 6G driven solutions. Based on the integrated role of AI and 6G, as discussed in Section V, it can be said that both will be highly utilized for delivery of immersive services in Metaverse while tackling the density and mobility of users. However, in order to meet the Metaverse requirements for ubiquitous intelligence from anywhere at anytime, 6G networks will require abundant resources and their maintenance [257]. While some of the resources might be highly leveraged, the others will rather remain redundant or unutilized most of the time, hence consuming the equivalent energy. To address this, network resources should be either adaptive or designed specifically according to the energy requirements of a certain Metaverse application [221], [223]. Moreover, since most of the intelligence will be hosted locally, it will consume relatively higher energy than cloud-based intelligence, and will eventually cause the batteries to drain faster. In such cases, the end devices should be capable of harvesting energy from their surroundings in order to remain self-sufficient [307]. Apart from that, modern AI models require significant energy for their execution due to their nature of being highly parameterised. Therefore, a potential research direction would be to either remove the redundant parameters from AI models by trading the accuracy or adaptively offload the models to edge or cloud based on the intermittent energy available on the devices.

D. TOWARDS SUSTAINABLE METAVERSE

This subsection highlights the foreseeable challenges and future directions concerning sustainable Metaverse.

1) CLIMATE CHANGE

Although the Metaverse has the potential to reduce carbon emissions, substantially through the virtual interactions and digital presence, but it can also be harmful to the environment if used improperly. For instance, with the emergence of Metaverse, there would be a need to power up data centers, thus the companies adopting Metaverse would need to shift to hyperscale data centers for meeting energy demands. Furthermore, most of the ecommerce associated with Metaverse is performed through NFTs and blockchain based processes which is an energy intensive process. Metaverse would need to move towards proof-of-stake

where the transactions are concerned as they are less energy intensive. Furthermore, AI can be used to optimize the efficiency gains while proof-of-stake transactions are performed to further lower the energy consumption.

2) DIGITAL DIVIDE

Studies have suggested that certain part of societies have better access to technology, therefore, the introduction to new technology in the market foster homogeneity instead of diversity. For instance, statista reported that Western Europe and North America makes up almost 90 percent of the VR set sales.⁴⁵ Very recently, PR Newswire suggested that North America will be the epicenter of Metaverse growth in next four years.⁴⁶ In order for Metaverse to be compliant with sustainable development goals, it needs to move forward towards equitable distribution of the technology, thus, lowering the digital divide in the digital world.

3) RESENTMENT AND DIVISION

Currently, the Metaverse is considered to be an extension of our reality or a digital space which is not dependent on the current mental state. However, continuous exposure and overuse of the Metaverse can create societal implications such as creating a parallel reality that affects the mental state and well-being of an individual. In order to make Metaverse sustainable, it needs to undergo governance and audit, so that an individual's mental state should not be overwhelmed and the individual's perception of digital world, i.e., Metaverse should be disjoint from its physical state, accordingly.

4) SECURITY AND PRIVACY

The Metaverse not only collects two-dimensional Internet data but also the three dimensional environment data, which, if leaked can have serious implications in the physical world. Furthermore, the Metaverse enables the users to create their multiple personalities which can elevate the challenge of security and privacy to manifold. The use of AI and blockchain for not only managing personalities, identities but also that governance, data ownership, authentication and transactions needs to be undertaken.

XI. CONCLUSION

This survey paper provides a comprehensive review on the role of AI and 6G in realising the immersive experiences of Metaverse. In particular, we investigated several underlying technologies of AI and 6G, such as advancements in computer vision, learning paradigms, and wireless communication technologies in the context of Metaverse. Besides that, we explore the joint role of AI and 6G technologies in obtaining ubiquitous intelligence, tactile feedbacks, and self-optimising capabilities for several Metaverse services

ranging from holographic telepresence to remote surgeries. Next, we highlight the sustainable aspect of Metaverse services followed by the applications, usecases, and on-going projects. Lastly, we enlighten numerous open issues, future directions, and lessons learned for potential researchers and developers of Metaverse applications and services.

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